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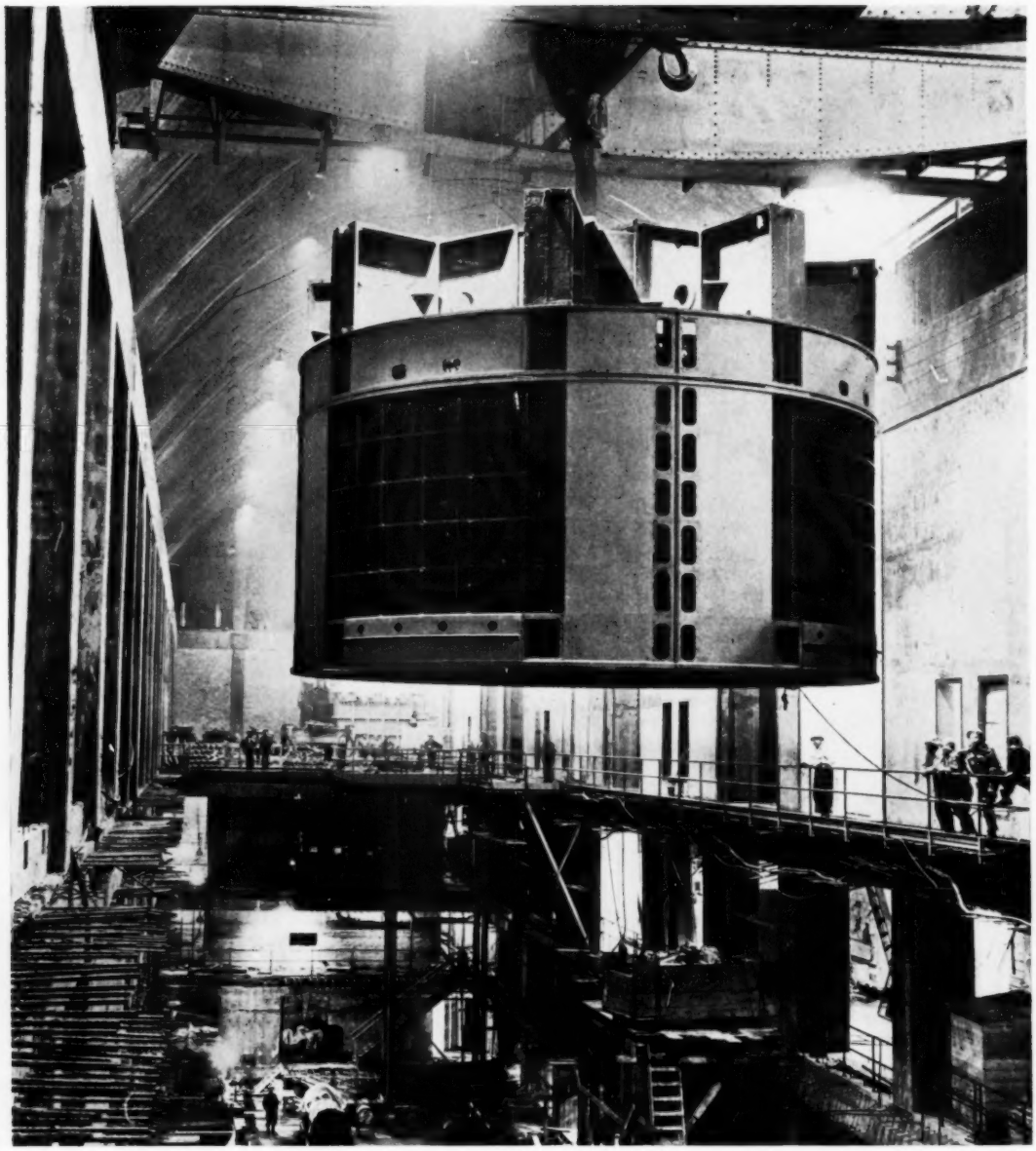


The stator of the 106,000 *kVA 'English Electric' alternator being lowered into position in the Kemano underground power station, British Columbia, of the Aluminum Company of Canada*

The New Technique of Underground Hydro-Electric Power Stations

By CHARLES JAEGER, Dr. es Sc. tech., Consulting Engineer to the Hydraulic Department of The English Electric Company, and Special Lecturer at the Imperial College of Science and Technology, London.

This article is based on lectures given by the author in Canada between April, 1954, and January, 1955; to the Instituto Superior Tecnico at Lisbon and the University of Oporto in June, 1954; and to the Société Royale Belge des Ingenieurs et des Industriels in February, 1955. Appreciable portions of the information given are similar to that contained in the author's paper to the Institution of Civil Engineers entitled 'Present trends in the design of pressure tunnels and shafts for underground hydro-electric power stations' and published in Part I of the 1955 Proceedings of that Institution.

RECENT STATISTICS SHOW that about one-third of the electric power consumed in the world is generated by hydro-power[1].

In recent years the trend towards new hydro-electric developments has been quite considerable, and it will be even more so in the next ten or twenty years. A substantial proportion of these modern developments is or will be underground power stations.

It is not uncommon for engineers to be faced by new techniques, overshadowing an older well-established practice. It is worthwhile for them to investigate the causes of the new techniques and methods to develop.

I. HISTORIC DEVELOPMENT OF THE TECHNIQUE OF UNDERGROUND HYDRO-ELECTRIC POWER STATIONS[2]

Underground power stations have been built for many years. The first to be mentioned is that of Snoqualmie (10,000 h.p.) in the State of Washington, U.S.A., in 1898, and shortly afterwards Brechbergmuehle in Germany (1907). Porjus in Sweden is dated 1914, and the powerful station of Brommat in the French Massif Central 1928-31. During this whole period underground power stations were the exception which did not forecast the sudden popularity of this new type of design with hydro-power engineers after the last war. When shortly after the end of the war hydro-power engineers were able to meet again at international congresses and to travel all over Europe, they found that different types of underground power stations had been developed in the Scandinavian hills and the European Alps. Typical for Swedish conditions was the power station of Krangede.

At the third Congress on Large Dams at Stockholm (1948), hydro-power engineers from many countries were shown the latest developments of the Swedish tunnelling technique and their application to the impressive developments of Harspranget and Hjalta (see Table VIII). The Swiss were proud of showing Innertkirchen, and the Edison group (Milan) and the Società Adriatica di Elettricità (Venice) could each show several most interesting prototypes of the new technique.

In recent years the trend towards underground power stations has been accentuated.

One of the great projects of Electricité de France—the Isère-Arc power station near Albertville, Savoie—is an underground station. In the case of the Roselend project, also in the Savoy Alps, where there is an available head of 1,171

[1] *Charles Jaeger. 'The hydro-electric industry.' English Electric Journal, Vol. 13, No. 8, December 1954.*

[2] *Charles Jaeger. 'Present trends in the design of pressure tunnels and shafts for underground hydro-electric power stations.' Proc. Institution of Civil Engineers, London, Part I, March 1955.*

metres, one of the most promising alternative designs is that of an underground station. Other examples are the enormous Kemano underground scheme (1,120,000/2,240,000 h.p.) now under construction in British Columbia by the Aluminum Company of Canada (Alcan), the no less important Bersimis scheme (1,600,000 h.p.) in the Province of Quebec, and the Snowy Mountains Tl Scheme in Australia[3], all of them in the British Commonwealth. Considerable developments are under way in Sweden, Norway and Italy.

The total capacity installed underground was said to be more than 7,000,000 h.p. in 1949, and must now be more than 11,000,000 h.p. if the installations in the near future at Kemano and Bersimis are included.

A number of underground power stations have been connected to conventional pressure pipe lines, and, in several cases, lined pressure shafts have been connected to surface power houses. In the great majority of cases, however, underground power houses are connected to lined pressure shafts or galleries so that the simultaneous treatment of both in the same article is entirely justified.

In 1948 it was predicted that 500,000 horse-power would be the maximum transmission through a single steel-lined pressure shaft. That figure has already been exceeded at Kemano, and projects are being considered which will raise the maximum to 1,000,000 h.p.

II. REASONS IN FAVOUR OF THE NEW TYPE OF UNDERGROUND POWER STATIONS (Fig. 1)

It was often said that hydro-electric power stations are put underground for fear of war-time action or bombardments. The rock overburden is supposed to give them full protection against bombs. The last war has shown that electric power stations are not chosen targets for bombs. Damage done to any part of a large electric grid is easily made good by switching the load to another part of the grid. Even in Scandinavia, where this aspect of the new technique has been carefully considered, any project is judged on its own merits and final decision will depend on the cost estimate as compared with alternative above-ground solutions. In few cases has any government been prepared to pay more for a station to be underground for purely military reasons. In most cases the selection was for purely technical or financial reasons.

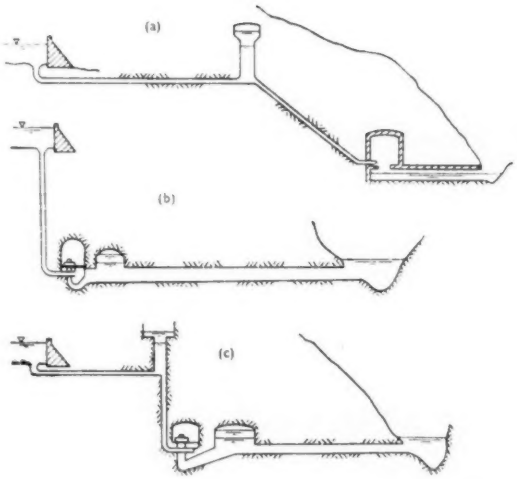


Fig. 1.—*Head-race arrangement* (*a*), *tail-race arrangement* (*b*), *and intermediate solution* (*c*)

The technical or financial points in favour of an underground design are not always the same. They may be summarised as follows :—

(*a*) In some cases the underground solution is better suited to the contour lines or the local geologic conditions. There may be no appropriate site for the classical arrangement with surge tank and steel penstock, or for location of the power house in a narrow valley endangered by avalanches.

(*b*) Consideration given to climatic conditions may be decisive in choosing the alternative. Work underground is carried out at a nearly constant temperature, regardless of outside climatic conditions. In very cold winter climate, work underground will proceed all the year round even when outdoor work will have to be stopped because of the cold.

[3] *The English Electric Company supplied a* 106,000 *kVA generator for Kemano. Four* 176,000/200,000 *b.h.p. turbines for Bersimis and two* 110,000/139,000 *b.h.p. turbines for Snowy T1 have been ordered recently.*

(*c*) An underground power station can be built in sound rock only, but then, thanks to the modern technique of tunnelling, may cost no more than an ordinary power house, according to local topographical or geological conditions.

Dr. Kaech had an opportunity to compare the costs for the stations at Handeck (surface machine house) and Innertkirchen (underground machine hall), both built in the same valley by the Oberhasliwerke (Switzerland). In order to construct the Innertkirchen machine room, together with its valve chamber, entrance and cable tunnel ventilating shafts and discharge tunnel, it was necessary to blast out no less than 60,000 cubic metres of rock.

Taking into account the maximum output of the completed station which has five sets of generating plant having a designed output of about 280,000 horse power, this gives a figure of 4·7 h.p. per cubic metre of enclosed space, or 3·45 kW per cubic metre, or 2·65 kW per cubic yard. For Handeck power station the equivalent figure was only 2·9 h.p. per cubic metre. The actual cost of constructing the Handeck station, with the access road and discharge canal, was about 2,300,000 Swiss francs for approximately 42,000 cubic metres of enclosed space, or 55 francs per cubic metre.

For Innertkirchen the cost was about 3,450,000 francs for 60,000 cubic metres, or 62 francs per cubic metre. The cost of the turbine house at Handeck, without the electro-mechanical equipment, was approximately 19 francs per horse-power installed, whereas equivalent figures for Innertkirchen are 13 francs per horse-power installed.

From these comparative figures it is clear that an underground power station, suitable for the Innertkirchen conditions, costs no more than erecting a complete power station in the open. The designer of Kemano underground station in Canada arrived at the same conclusion. Furthermore, it may be mentioned that at Etzel power station (Switzerland) 6,300 tons of steel were required for the pipeline, whereas for Innertkirchen, which has a higher head and a similar length of pressure shaft carrying the same quantity of water, only 1,300 tons of steel reinforcement were required for the shaft.

In other cases an unlined tailrace tunnel may be cheaper than a lined headrace pressure tunnel, especially if the latter has to be reinforced or steel lined. Recently, pressure tunnels (Maggia, Kemano) have been kept unlined over large distances. Economic and financial advantages are at the root of modern underground power stations.

(*d*) Very high concentration of power in one installation is possible with underground power stations.

(*e*) Power stations and penstocks being underground, there is no danger of spoiling the scenery. In cases such as Clachan (Scotland) or Rheinau (Switzerland) where it is essential not to spoil the amenities of the landscape, subterranean power houses and pipes are the obvious choice.

Arguments in favour of underground power stations do not explain their recent popularity with engineers, unless it is pointed out that improvements and developments in the general technique of tunnelling made possible the huge excavation work and concentration of power in few large stations. Tunnelling is nowadays a highly mechanised process and very high rates of progress can be achieved. Table I gives an idea of modern tunnelling achievements.

TABLE I[4]

WEEKLY FOOTAGE ACHIEVED AT KEMANO MAIN PRESSURE TUNNEL

Heading	Equipment	Footage	Date
Kemano ..	Heavy	248	28th September, 1952
Kemano ..	Heavy	261	1st November, 1952
West Tahtsa ..	Light	272	2nd November, 1952
Horetzky ..	Heavy	274	29th November, 1952
Horetzky-Kemano ..	Heavy	282	21st February, 1953

This table refers to the weekly footage (6-day week) achieved with Ingersoll Rand heavy equipment and Atlas Copco light equipment in good

[4] *Table I is from 'Tunnelling operations on the Alcan Project.' Water Power, Vol. 6, No. 5, May 1954. See also The Engineering Journal, Montreal, Vol. 37, No. 11, November 1954.*

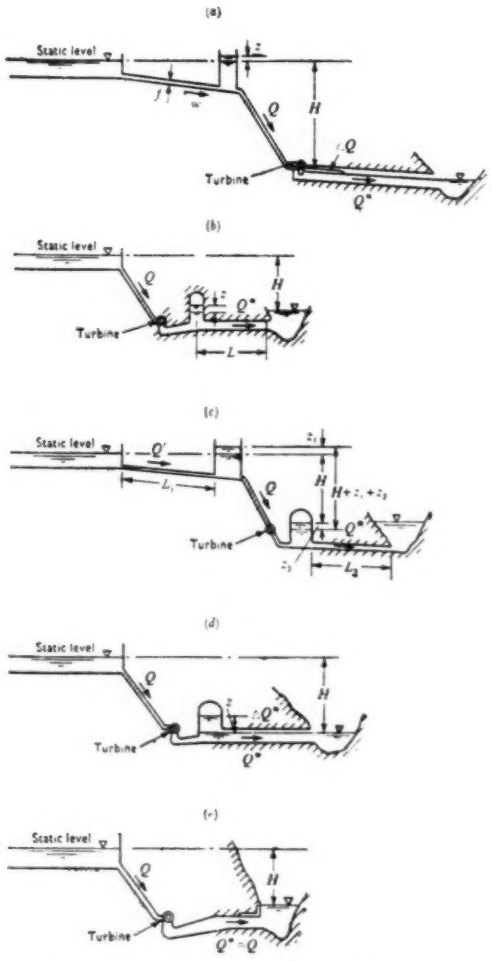


Fig. 2.—Five principal hydro-dynamic types of underground hydro-electric power station

rock. Progress with the Atlas Copco equipment was found to be cheaper.

Many other proofs of the efficiency of modern tunnelling methods could be given: the excavation of the cavern for the Kemano machine hall was a success. These are examples for good rock conditions. The tunnelling of the Malgovert pressure gallery is an example of what can be done, within reasonable limits of costs, when the rock is extremely bad.

A final argument explaining the success of this modern technique of underground power stations is the necessity of concentrating more and more power in huge developments. The power output of a conventionally designed pipeline is limited. From existing examples (Table III) and from theoretical calculations, it is to be seen that the power output of steel-lined pressure shafts is much higher.

III. HYDRO-DYNAMICS OF UNDERGROUND POWER STATIONS

One of the main points in favour of underground designs—which has still to be made clear—is their great flexibility in meeting the requirements for turbine governing. In some difficult cases this argument was found to be the determining factor in favour of underground stations. A well-known classification of underground stations is based on the hydro-dynamic characteristics of different schemes, especially with regard to governing conditions. In this classification there are the following five types[5] (Fig. 2) :—

(*a*) The tailrace tunnel is a free level tunnel, without a surge tank downstream (Innertkirchen, Clachan, Krangede, Isère-Arc[6]).

(*b*) The tailrace tunnel is a pressure tunnel with a conventional surge tank on the tailrace ; there is no surge tank on the upstream side (Harspranget[7]).

(*c*) The whole system is under pressure, with surge tanks on both sides of the turbine. In this case the behaviour of the system will depend on whether the turbine is of the reaction or impulse type.

(*d*) Free flow exists in the tailrace tunnel during normal steady conditions but the tunnel will fill up during major disturbances in the flow conditions. In such a case the tank is called a 'partial working' surge tank (Wettingen type).

[5] *Charles Jaeger. 'Underground hydro-electric power stations.' Civil Engineering and Public Works Review, Vol. 43, p. 620, December 1948, and Vol. 44, p. 38, January 1949.*

[6] *G. F. W. Adler. 'Model tests on Clachan underground power station.' English Electric Journal, Vol. 11, p. 119, June 1950.*
Charles Jaeger' 'The Isere-Arc Development.' Water Power, Vol. 3, p. 256, July 1953, and p. 301, August 1933.

[7] *G. Westerberg and B. Hellstrom. 'Swedish practice in water power development.' Paper No. 2, Section H1, Fourth World Power Conference, 1950, Vol. 4, p. 2071.*

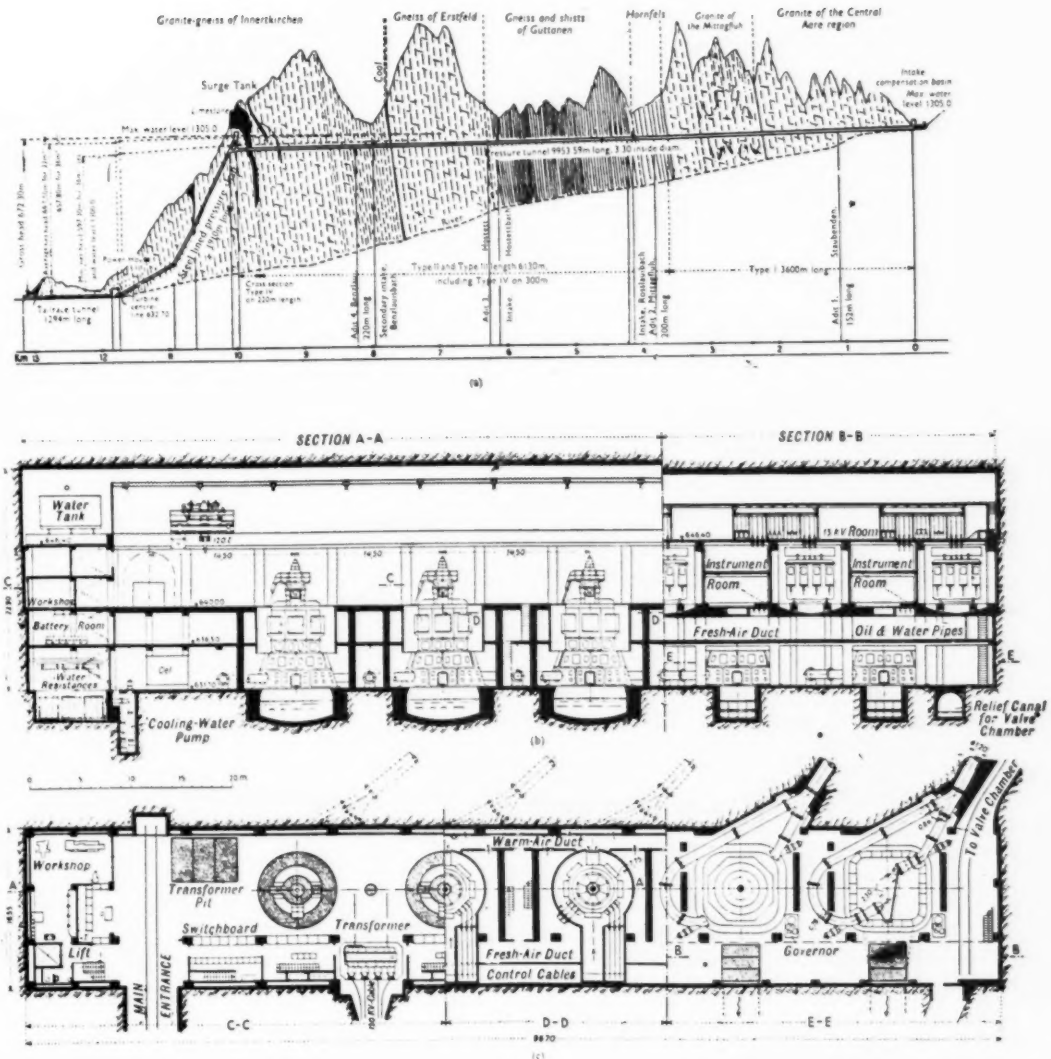


Fig. 3.—The Innertkirchen scheme in Switzerland: (a) Longitudinal section showing layout of scheme (b) Longitudinal section through the underground power station (c) Plan of the underground power station

(Illustration (a) by courtesy of Schweizerische Bauzeitung, and illustrations (b) and (c) by courtesy of Wasserkraft und Wasserwirtschaft)

(*e*) Finally the whole system, if very short, can be fully under pressure without any surge tank.

Before giving any explanation of these five typical cases, it must be said that the governing of a turbine requires rapid closing or opening of the turbine gates, which provokes rapid deceleration or acceleration of the discharge and causes heavy pressure variation in the pipes, called 'water hammer.' The water hammer may be

reduced if a surge tank of convenient dimensions is introduced at the right place along the pressure conduits. Unstability of governing may be caused by an unhappy ratio of the pipeline length to the turbine head or by severe water hammer conditions. Another cause of unstable governing may be inadequate dimensions of the surge tank, preventing the surges being enabled to damp out. There is a certain minimum area of the horizontal cross-sections in the tank for the surges to be stable, or better, to damp out rapidly. This area is called the ' Area of Thoma,' which is a major point to be investigated for heads of about or less than 100 metres.

(a) **Free Level Tailrace Tunnel without Downstream Surge Tank** (Fig. 2a)

The first way to design an underground power station is to build the tailrace tunnel large and steep enough to permit any discharge to pass without putting the tunnel under pressure, both for steady flow conditions and for unsteady flow conditions producing translatory waves. Conditions for such a solution to be possible are realised if enough head is available. This type of arrangement is usual with Pelton wheels (impulse turbine) sometimes in connection with an upstream surge tank, which then does not interfere with the flow in the tailrace tunnel. Many examples with reaction wheels can also be mentioned.

A very interesting example of this type is the Innertkirchen (Switzerland) power station (Fig. 3). The gross head is 672·30 metres (2,205 ft), the length of the pressure tunnel being 10,000 metres (32,808 ft). The total discharge of the 5 Pelton turbines (428 r.p.m.) is 46 cubic metres per second (1,630 cusecs). The slope of the 1,400-metre-long (4,593 ft) tailrace tunnel is 0·25 per cent. It has been calculated, and confirmed by model tests, that this discharge, as well as any wave produced under unsteady conditions, will pass without putting the tailrace tunnel under pressure.

Under steady flow conditions the water surface in the tunnel is given by an ordinary draw-down curve, and for unsteady conditions by the calculation of translatory waves. The classical theories of waves are given for rectangular canals. These can easily be extended to the case of horse-shoe tunnels which is the usual shape for tailrace tunnels.

Krangede power station (1936-1942), see Figs. 4 and 5, with 8 Francis turbines (1,500,000,000 kWh per annum) and with a head of about 60 metres (197 ft) and two tunnels 1,500 m long (4,921 ft), is an early example of this type equipped with reaction wheels. Downstream of the power house there is an air shaft, but this does not work as a surge shaft, the flow in the tunnel remaining a free level flow. There is no headrace tunnel and no headrace surge tank. Other examples are Clachan (Scotland) and Verbano (Switzerland).

Most of these power stations have been designed to avoid any flooding of the generator floor, even under the most dangerous conditions which might occur after the breakage of a pipe, which is most improbable with the penstocks built entirely in the rock.

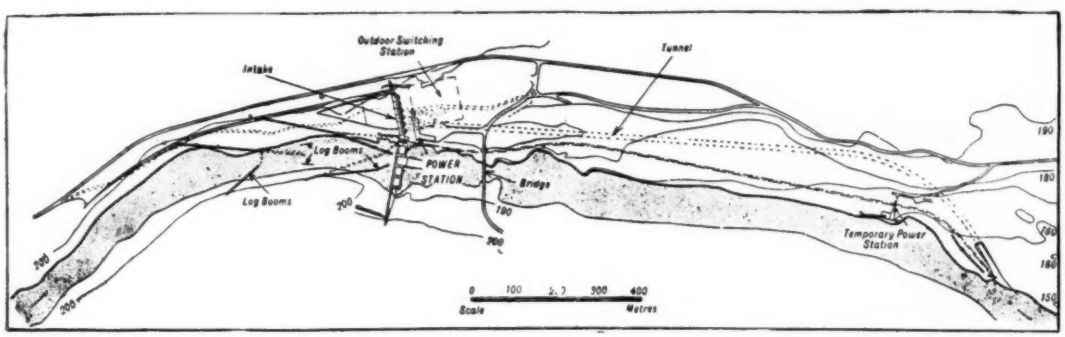


Fig. 4.—General arrangement of the Krangede development in Sweden

(Illustration by courtesy of 'The Engineer')

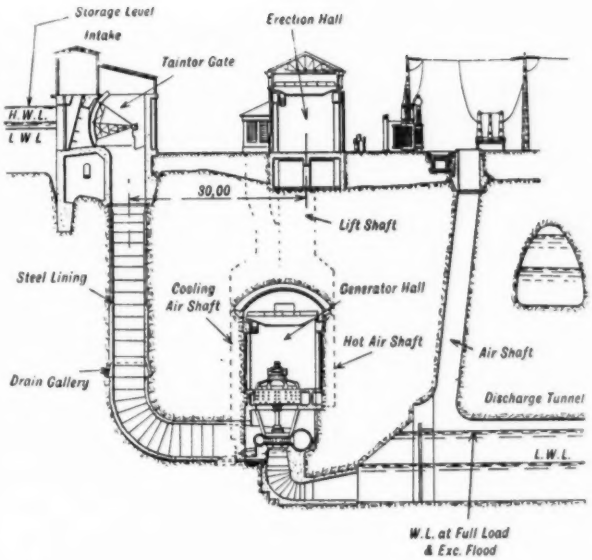


Fig. 5.—The Krangede development : cross-section through power house and tunnel

(Illustration by courtesy of 'The Engineer')

(b) **Tailrace Pressure Tunnel with Normal Working Downstream Surge Tank** (Fig. 2b)

In this case there is no upstream surge tank, but a tailrace pressure tunnel and a downstream surge tank, and their dimensions can be calculated by the ordinary classical equations of surges. The limiting condition of Thoma for stable governing applies to this type of surge tank as for an ordinary surge tank. The turbines will usually be of the reaction type, and the level of the pressure tunnel entrance has, whenever possible, to be chosen so that no air can enter the tunnel when the level in the surge tank is oscillating.

This solution would be the best when the tail water level varies widely with flood conditions. It would also be advantageous if, owing to varying level in the reservoir, the alternative solution with upstream pressure tunnel and surge tank is too expensive because of the high pressure in the tunnel and the height of the surge shaft. It has also been considered in some cases where topographical conditions do not suit a headrace surge tank.

From the data which is available on the large Swedish underground power stations built after the last war (Harspranget and Hjalta), it is assumed that they are of the type described in the preceding paragraphs. The Glen Moriston station now under construction in Scotland is also of this type.

The theory of surges in downstream surge tanks is similar to the classical surge tank theory, some algebraic signs being reversed.

(c) **Systems with Headrace and Tailrace Surge Tanks** (Fig. 2c)

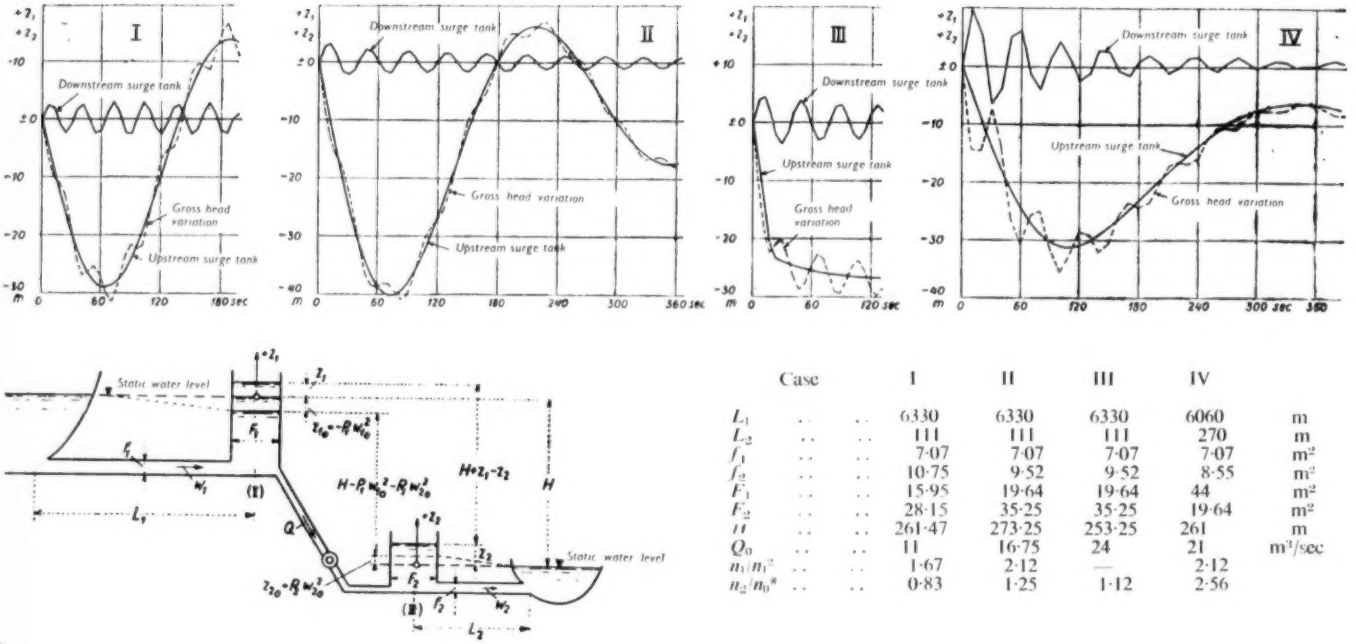
At Innertkirchen, Montpezat, etc., the conditions at the tailrace were not interfered with by the existing headrace surge tank. In all these cases the turbines used or proposed were of the impulse type. Recently several power stations have been developed with both headrace and tailrace tunnels under pressure separated by a reaction turbine. It is obvious that oscillations in both tanks would mutually interfere, so that the problem of damping the oscillation becomes very important, and had to be dealt with in detail.

It was found that to avoid instability of oscillation in such a system, the minimum areas for both the headrace and the tailrace surge tanks had to be multiplied by a factor which in some cases could be larger than 2 or 3. How the oscillations of both surge tanks depend on the dimensions, as compared with this new stability condition, is shown on Fig. 6.

(d) **Tailrace Tunnel with Partial Working Surge Tank** (Fig. 2d)

It has been stated that tailrace surge tanks should satisfy the stability condition of Thoma if the load is regulated. If the head is low and the discharge large, this condition leads to very large tank areas.

At Wettingen on the River Limmat in Switzerland, the tailrace crosses a hill so that, though the power house is built in the open, operating conditions are the same as in an underground power house. The discharge through the three turbines is 129 cubic metres per second (4,238 cusecs) and the tunnel length is 457 metres (1,499 ft), the horseshoe section tunnel width being 8·50 metres and



Case	I	II	III	IV	
L_1	6330	6330	6330	6060	m
L_2	111	111	111	270	m
f_1	7·07	7·07	7·07	7·07	m²
f_2	10·75	9·52	9·52	8·55	m²
F_1	15·95	19·64	19·64	44	m²
F_2	28·15	35·25	35·25	19·64	m²
H	261·47	273·25	253·25	261	m
Q_0	11	16·75	24	21	m³/sec
n_1/n_1^*	1·67	2·12	—	2·12	
n_2/n_0^*	0·83	1·25	1·12	2·56	

Fig. 6.—Oscillation in a system of two surge tanks
(Illustration by courtesy of Schweizerische Bauzeitung)

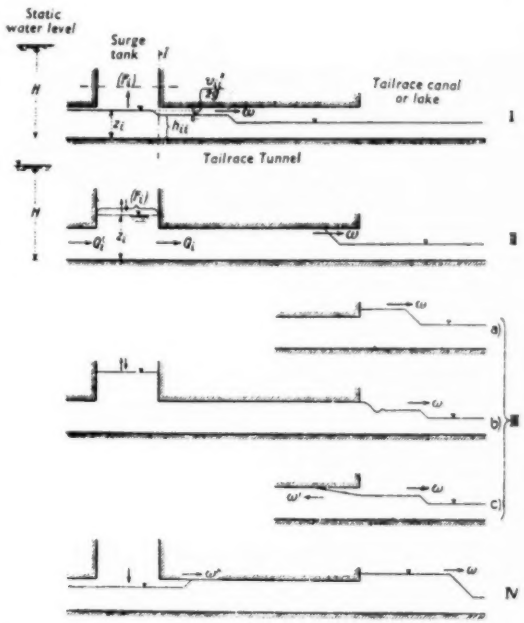


Fig. 7.—The Wettingen power development in Switzerland : different phases of surge

(Illustration by courtesy of Schweizerische Bauzeitung)

its height 7·70 metres (27 ft 11 in by 25 ft 3 in). The level in the Limmat downstream of the tunnel end varies between R.L. 356·95 and R.L. 358·65, the gross head being 21·60 metres to 23·30 metres (70 ft to 76 ft 5 in). It was found there that a surge tank large enough to meet the requirements of the Thoma formula was too expensive. An alternative scheme with a free level tunnel able to absorb any translatory wave would not have been cheaper. It was then proposed to build a ' partial working ' surge tank : that is, the tunnel was to be built just large enough to allow steady flow of the maximum turbine discharge during high water conditions in the River Limmat at the downstream end of the tailrace, but unsteady flow conditions produced by the opening of the turbines would soon put the tunnel under pressure by the formation of positive waves. To meet these unsteady flow conditions, a surge tank was to be built in which the water could rise and afterwards fall. By the fall of the water level in the surge tank, back to steady level, the tunnel becomes a free level tunnel again, and the surge tank is put out of operation, the water no longer rising (Fig. 7). Under such conditions it is obvious that the condition of Thoma does not apply to a ' partial working ' surge tank, so that the dimensions of the Wettingen surge tank could be chosen far smaller than those of the first project with an ordinary tailrace surge tank.

To avoid any damage to the generators, the water in the surge tank must never rise enough to reach the generator floor, so giving a clear limiting condition for the problem.

All the calculations for the Wettingen surge tank and tailrace tunnel were made with the equation of momentum, the use of which for a problem of this description was, at that time, very new. The theory resulted in a combination of the surge tank theory with wave calculation. A model was then built and it was ascertained that the results of the tests agreed with the mathematical analysis. The Wettingen power station was built on this basis, and has been in operation since 1932 without trouble.

At Wettingen the downstream outlet of the tunnel was always working free ; that is, the highest water level in the Limmat River remained below the top of the tunnel, allowing a free escape of any air trapped in the tunnel and to the front of the translatory waves running down the tunnel.

In other schemes it may be that in some cases the tunnels have to operate momentarily fully under pressure, if flood conditions are ruling at the downstream end. In these cases the area of the surge tank has to be somewhat larger than the limiting value given by Thoma.

(e) Systems Fully Under Pressure with no Surge Tanks (Fig. 2e)

This last alternative will be considered for designs with very short pressure pipes and galleries, the typical example being a power station by-passing a dam, the station being underground because of lack of space at the toe of the dam. This arrangement having no surge tanks, there are no surges and no surge instability. Unsteady flow condition will cause pressure waves of the elastic type or water hammer to be produced in the pipes. The problem will be to estimate the pressure rise and the pressure drop caused by water hammer, and to check the conditions for turbine design and turbine regulation.

TABLE II

DATA ON LARGE STEEL-LINED PRESSURE SHAFTS

Name	Country	Date of commission	Gross head : m	Internal dia. : m	Rock	No. of pipes	Discharge : cumecs	Gradient : tan α
Lavey	Switzerland	1950	42·5	5·8	—	3	200	—
Porjus	Sweden	1914	57	3·5-42	Granite	7+2	90	Vertical
Niagara ..	U.S.A.	1920	60	4·7	Limestone	1	—	Vertical
Krångede ..	Sweden	1936	60	5·5	—	4	—	Vertical
Niva	U.S.S.R.	1949	74	4·5	—	4	4×62·5	Vertical
Castillon ..	France	1949	90	3·4	Good limestone	2	72	0·35
Cordéac ..	France	1946	92·5	2·9–3·8	Limestone	1+1	29+28	0·71–0·02
Châtelot ..	France	—	91	3·0	Limestone	1	40	0·702
Piage-de-Vizille	France	1950	142·4	3·5	—	1	45	0·549
Isère-Arc ..	France	1953	153	2–3·7	Gneiss, mica-schists	2	2×50	Vertical
Salarno ..	Italy	1945	162	1·6–2·0	—	1	3	Vertical
Boulder ..	U.S.A.	1936	177	9·14–7·62 3·96–2·59	—	—	—	1·00 0·70
Valabres ..	France	1954	195	2·2	Limestone	1	15	0·85
Sillre	Sweden	1923	197	1·85	—	1	—	0·19
Soverzene ..	Italy	1948	285/225	2·55	—	2	2×20	3·00
Brevières ..	France	1951	232	3·75	Quartzites	1	50	0·02
Cedegolo ..	Italy	Constr.	234	2·60	—	—	—	Vertical
Rossaaga ..	Norway	Constr.	245	3·3–2·8	—	1	34	1·00
Brommat ..	France	1933	260	4·0–3·0–2·6	Granite	3	—	Vertical
Bersimis ..	Canada	Constr.	267	9·45 3·06–2·36	—	1 8	416 52	Horizontal 1·19–0·01
Wassen ..	Switzerland	1949	281	2·4–2·2	—	2	2×42	0·67–0·013
Castelbello ..	Italy	1949	294	3·25–2·80	—	1	21	0·85
Verbano ..	Switzerland	1953	297	3·0–2·80	—	1	44	—
Mera I ..	Italy	1948	330	2·55–2·25	—	1	—	0·70
Snowy Mountain T I	Australia	Constr.	336	3·65	—	2	2×64	Vertical
Rodund III ..	Austria	1943	339	3·2–3·05	—	1	60	0·58–0·0
Tafjord II ..	Norway	Constr.	396	1·75	—	1	60	0·93
Achensee ..	Austria	1927	406	2·3	Limestone (Dol.)	1	—	1·00
Cañon del Pato	Peru	Constr.	420	1·8	Granite	1	28	Vertical
Mauvoisin-Fionnay ..	Switzerland	Constr.	459	2·4	Calcar. schists	1	23	—
Handeck II ..	Switzerland	1950	463	2·25–2·15	Granite	1	30	0·61–0·15
Pallazeno ..	Italy	1926	527	1·8–1·5	Gneiss (mediocre)	1	8·4	0·70
Oberaar ..	Switzerland	1953	531	1·65	—	1	—	—
Handeck I ..	Switzerland	1932	546	2·3–2·1	—	1	8	0·72–0·08
Santa Massenza	Italy	1949	600	2·6–2·5	Limestone (excellent)	1	20	0·85
Gerlos	Austria	1943	620	2·2–1·6	Limestone (fissured)	2 1	2×35 12	0·52
Lyse	Norway	Constr.	630	2·0	Granite	—	—	0·70
Montpezat ..	France	1953	643·5	2·6	Granite	1	22	0·467
Innertkirchen ..	Switzerland	1940	672	2·6–2·4	Granite and gneiss	1	40	0·616 0·583
Rovesca ..	Italy	1926	720	1·2	Schists, gneiss	1	3	0·123 0·70
Mese	Italy	1926	758	1·8	Gneiss (mediocre)	1	—	0·70
Kemano ..	Canada	Constr.	790	3·35	—	4	4×62·5	1·11
Pfaffensprung ..	Switzerland	Proj.	823	2·5	—	1	4×30	0·70–0·60
Grande-Dixence-Fionnay ..	Switzerland	Constr.	872	3·0–2·8	—	1	45	—
Albigna ..	Switzerland	Proj.	1,046	1·5	—	1	—	—
Roselend ..	France	Proj.	1,171	3·0	Schists	1	50	0·90

Examples can be quoted for each type of design. The advantages or disadvantages of any solution have to be discussed in relation to the scheme under consideration. In addition, the designer has to choose between : reaction or impulse wheel, vertical or horizontal shaft, main gates (or valves) to be in the main power-house chamber or in a separate chamber, transformers underground or above ground.

IV. LINED PRESSURE TUNNELS AND SHAFTS

Lined pressure tunnels and shafts are intimately connected with the design of underground power stations, as already mentioned in Section I.

Many years ago, engineers were vastly impressed by the bold design of the great trans-alpine tunnels (St. Gothard and Simplon). Data were given at that time about the internal rock pressure and the creep of the rock ; examples were mentioned of tunnel linings being crushed by the rock pressure. These were interpreted by the theory of A. Heim (Zurich University) according to which, at great depths, the rock's own weight causes it to behave as a plastic material or even as a liquid ; the pressure around any point is the same in all directions and equal to the hydrostatic pressure, the density being that of the rock.

When, some years later, engineers were requested to design the first large hydro-power pressure galleries in rock, or to submit proposals for the first steel-lined shafts, they were strongly influenced by the unfortunate history of the Ritom tunnel, which had been damaged and dangerously fissured by internal water pressure.

Designers tried to develop theories explaining the strain and stress distribution in rock as a special case of the theory of thick cylinders. Not only did the two theories of rock deformation seem to have no connection whatsoever, but they seemed to contradict each other. Another theory was being developed, assuming that an empty tunnel in the rock is subjected to a vertical field of parallel forces, so contradicting the theory of Heim and obscuring the issue. However, it can now be appreciated that the theory of Heim for empty tunnels and the calculations of the stresses and strains developed around a pressure tunnel are intimately connected. It is probable that future design of underground power stations will depend largely upon the designer's ability to reconcile the two theories and to take advantage of modern pre-stressing developments.

An interesting example is the design of steel-lined shafts. It is very likely that the first steel-lined pressure shafts were built with little knowledge of

TABLE III

WATER-HORSE-POWER OF LARGE SHAFTS

Year	Power station	Head		Discharge per shaft		Power per shaft : h.p.	Total power : h.p.
		m	ft	cumecs	cusecs		
1942	Innertkirchen	672	2,200	40	1,410	325,000	325,000
1947	Lumiei	480·6	1,580	16·5	583	77,000	77,000
1951	Santa Giustina	183/95	600/311	22·2/15·9	780/562	142,500	142,500
1952	Santa Massenza	590/460	1,940/1,505	70	2,470	200,000	400,000
1952	Handeck II	463	1,515	30	1,060	154,000	154,000
1953	Isère-Arc	152	500	50	1,770	90,000	180,000
1954	Montpezat	634	2,080	22	779	162,000	162,000
1954	Kemano	790	2,597	62·5	2,210	560,000	2,240,000
Constr.	Bersimis	253	830	416	14,700	1,600,000/ 200,000*	1,600,000
Proj.	Roselend	1,171	3,840	50	1,770	660,000	660,000
,,	Pfaffensprung	820	2,690	30	1,060	245,000	980,000
Constr.	Grande-Dixence-Fionnay	872	2,860	45	1,590	390,000	390,000
,,	Mauvoisin-Fionnay	459	1,400	23	815	170,000	170,000
,,	Snowy Mountain T 1	336	1,105	128	4,530	270,000	540,000

* *The main shaft, 570 feet long, divides into eight penstocks.*

TABLE IV

CHARACTERISTIC DATA ON SOME GREAT STEEL-LINED PRESSURE SHAFTS

Power station	Country	Gross static head		Internal pipe diameter		Steel thickness		Stresses* in steel plate	
		m	ft	m	ft	mm	in	kg/sq cm	lb/sq in
Handeck I	Switzerland	550	1,800	2·10	6·89	20	0·79	2,885	41,000
Innertkirchen	,,	672·3	2,200	2·40	7·87	20	0·79	4,030	57,400
Innertkirchen test tunnel	,,	1,500	4,920	2·20	7·22	10	0·39	16,500	234,000
Handeck II	,,	463	1,520	2·15	7·05	12	0·47	4,150	59,000
Oberaar shaft	,,	531	1,740	1·65	5·41	13	0·51	3,380	48,000
Oberaar free pipe	,,	532·5	1,743	1·40	4·59	28	1·10	1,330	18,900
Wassen	,,	279·2	915	2·40	7·87	11	0·43	3,050	43,100
Gondo	,,	490	1,605	1·6	5·25	17	0·67	2,300	32,700
Verbano	,,	297	974	2·8	9·19	26	1·01	1,600	22,800
Piage-de-Vizille	France	142·5	466	3·5	11·48	11	0·43	2,270	32,200
Isère-Arc	,,	152	500	3·7	12·14	16	0·63	1,750	24,900
Kemano	Canada	790	2,597	3·35	10·99	49·3	1·95	2,670	37,900
Pfaffensprung (projected)	Switzerland	818·5	2,680	2·50	8·20	34	1·34	3,000	42,500
Abjora	Norway	442	1,450	2·30	7·55	22	0·87	2,310	32,900
Lyse	,,	630	2,067	2·0	6·56	18	0·71	3,500	49,700
Tafjord	,,	396	1,300	1·75	5·74	15	0·59	2,410	34,300
Rössaga	,,	245	804	2·8	9·19	23	0·91	1,500	21,350

* *At the bottom of the shaft, assuming that no load is transmitted to the rock.*

the actual stresses developing in the steel lining and in the rock. In the ensuing period, a rule-of-thumb method was used, according to which the stress in the lining was supposed to include the whole internal water pressure, neglecting any transmission of load to the rock, and should not exceed the yield stress of the steel plates. The steel lining was therefore calculated by means of the well-known formula for stresses in thin pipes using a high value for σ. This rule is still applied when the rock to be traversed is heterogeneous and somewhat unreliable. The linings of several modern shafts in the Italian Alps were calculated on similar assumptions (with σ = 1,600 to 1,800 kilograms per square centimetre). The effect of this rule is to reduce by more than a half the weight of steel to be used for the lining, as compared with the conventional pipeline of identical length, diameter, and pressure conditions.

Table IV shows the stresses which would develop in the steel lining of actual shafts on the basis of this simplified assumption.

In the years 1925 to 1930, theories were developed which took into account the relative elasticity of the steel lining, the concrete, and the rock, and considered the partial transmission of the water pressure from the steel lining to the concrete and the rock. The principle of this calculation is easily understood[8].

The water pressure p inside the conduit (Fig. 8) produces an expansion of the steel lining which is partially restrained by the concrete and the rock. If p_b and p_c denote the pressure transmitted in a radial direction from the steel to the concrete and from the concrete to the rock respectively, then the tangential stress in the steel lining is $\sigma = (p - p_b)\, b/e$, where b denotes the radius of the steel lining and e its thickness. If E denotes the modulus of elasticity, then the elastic radial displacement of the lining is $\Delta b = \sigma\, b/E$, which must be equal to the radial displacement of the concrete. A second system of equations is written for the radial displacements of the concrete and of the rock, which must also be equal. The two systems of equations yield the values of p_b and p_c and the stresses σ_r (radial) and σ_t (circumferential or tangential) at a distance R from the centre O.

[8] *Charles Jaeger. 'Théorie générale du coup de bélier.' Dunod, Paris 1933, pp. 119-130.*

The calculation shows that for small water pressures p (up to 5 kg per sq cm) and small diameters D (2·5 to 3·5 m) the tensile stress σ in the steel lining is low, even when the steel thickness e is small.

Many measurements of stresses in steel linings have confirmed this conclusion and so proved that the bulk of the load is taken by the rock, as foreseen by the theory. If the pressure or the diameter increases, the proportion of the load taken by the steel lining also increases.

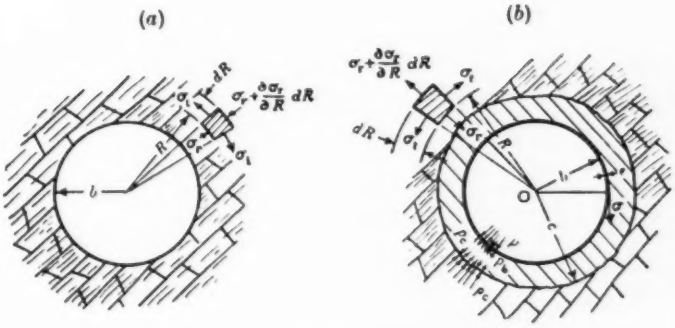


Fig. 8.—Stress distribution (a) in rock around an unlined pressure tunnel, and (b) between steel lining, concrete and rock in steel-lined pressure galleries

Another conclusion is that circumferential tensile stresses σ_t develop in the rock. The calculation also shows the great importance of temperature stresses and of any gap existing between steel lining and concrete lining before the tunnel or shaft is put under pressure.

Because of these tensile stresses in the rock, it was thought that there would be a limit to the dimensions of steel-lined pressure shafts. Theories regarding what would happen if radial fissures were to develop in the rock were propounded but were not convincing.

In contradiction to these theories, tensile stresses developing in the rock seem to have no effect on the stability of the lining; rock which should be fissured remains solid, and doubts may therefore arise with regard to the validity of the theories unless they are corrected including for the natural pre-stressing of the rock.

Up to the present no failure of steel linings arising from the development of rock fissures has been reported, but failures of the lining have been caused by external water pressure, by grossly defective design, or by lack of homogeneity of the concrete filling between the steel lining and the rock.

Direct proof that the strained rock behaves quite differently from what could be expected from the theory is given by the behaviour of three Italian pressure shafts designed as early as 1925-26 by Marinoni, the characteristic data of which are given in Table V. These three shafts are lined with corrugated steel plates, the thickness of which is less than 4 mm ; these cover an ordinary concrete lining. The stations have been in operation for 25 years and the accidents which have occurred to the shafts have all been caused by outside pressure and were quickly repaired. This experience shows that in some cases the whole hydrostatic load can be transmitted to the rock, the steel lining serving only as a water-tight sheath.

TABLE V

SHAFTS DESIGNED BY MARINONI

	Head		Diameter of shaft		Rock	Theoretical value of σ_t in rock	
	m	ft	m	ft		kg/sq cm	lb/sq in
Pallanzeno ..	527	1,730	1·80 to 1·50	6 to 5	Gneiss	− 52·7	− 750
Rovesca	720	2,360	1·20	4	Schists and gneiss	− 72·0	− 1,025
Mese	758	2,490	1·80	6	Gneiss (not compact)	− 75·8	− 1,075

The theoretical values calculated for σ_t in Table V are higher than those which would normally be assumed for a homogeneous rock, and much higher than for a fissured rock.

Clearly, therefore, the ability of rock to withstand the tensile stresses σ_t is far greater than was expected. As a result new theories had to be evolved on the basis of extensive research and measurements, and these are of great importance for the technique and design of pressure shafts.

Most of this new research work assumes, either explicitly or implicitly, the validity of the old theory of Heim concerning the internal compression stresses already present in rock prior to any excavation. This rock pressure, which at some greater depth may be approximately the same in any direction at any particular points, is, in the mind of the designer, equivalent to a natural pre-stressing of the rock. This natural pre-stressing may more than compensate the tensile stresses induced by the water pressure in the tunnel.

A tunnel or shaft will be safe if the resultant stresses at any point of the steel lining or at any point of the rock, including the effect of natural or artificial pre-stressing, are well inside the known permissible values.

These introductory remarks on the theories of rock behaviour will make it easier to present the more detailed analysis of the complicated conditions prevailing in lined and unlined pressure tunnels and shafts.

The next logical steps in the discussion of this subject are consideration of the constructional materials available and an analysis of the behaviour of concrete, steel, and rock. Rock is by far the most important material, and very little is yet known about its behaviour *in situ*.

Rock Strength and Elasticity

Natural rock is the most important material in steel-lined pressure shafts, since it carries most of the pressure loading. Being well aware of visible or assumed faults in rock, civil engineers show some hesitation in permitting it to be subjected to a high proportion of the water pressure stresses.

The crushing strength of sound rock, as ascertained from unfissured rock, is often very high. Values of up to 2,000 kg per sq cm have been obtained from Urseren granite (Swiss Alps). The crushing strength is greatly increased if a transverse strain is applied. A rock sample showing a crushing strength of 300 kg per sq cm will have its strength raised to 600 kg per sq cm if a transverse stress component of 100 kg per sq cm is applied.

If the rock is fissured, then its crushing strength is not decreased so long as the angle $\frac{1}{2}\pi - \alpha$ between the direction of the compression stress σ_1 and the direction of the fissures is such that $\alpha \leq \varphi$, where φ is the angle of friction between rock and rock. Obviously, $\alpha = \varphi$ is a limit value at which the conditions of equilibrium of the sample will change. If $\alpha > \varphi$ and if no strain component acts in a direction perpendicular to σ_1, the sample shows no resistance to the compression force.

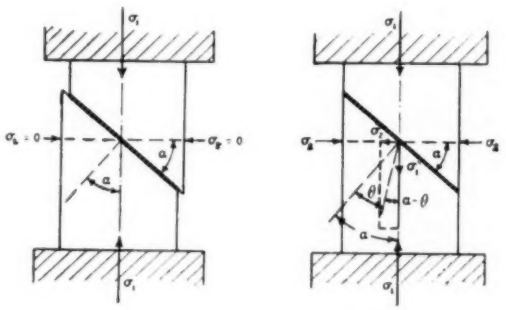


Fig. 9.—Lateral stress in fissured rock

When a stress σ_2 perpendicular to σ_1 is introduced, then, according to Fig. 9 the angle θ of the stress φ resulting from σ_1 and σ_2 must be $\theta \leq \varphi$. Then $\sigma_2 = \sigma_1 \tan(\alpha - \theta)$ and therefore $\sigma_2 \geq \sigma_1 \tan(\alpha - \varphi)$.

In 1923 the pressure tunnel of Ritom in Switzerland was severely damaged by cracking, attributed to yielding of the rock. Measurements were made in the tunnel of Amsteg in order to determine the modulus of elasticity of the rock *in situ*. These measurements were probably the first to be published on this subject. Later on, similar tests were repeated in many tunnels (Lucendro, Malgovert, Rossens, Italian tunnels, etc.), sometimes in conjunction with the construction of large dams but mainly in order to get first-hand information on the behaviour of pressure tunnels. The results

obtained showed that the modulus of elasticity E depends not only on the rock type and quality but also on the direction of the force, E being smaller in the direction perpendicular to the strata than in the direction parallel to the strata. The measured values in both directions are :[9]

	Normal to strata: kg per sq cm	Parallel to strata: kg per sq cm
Rossens sandstone ..	22,000	50,000
Urseren granite ..	250,000	400,000
Urseren schists ..	80,000	280,000

There is an interesting comparison between these figures and the value of E measured at Chimbote in Peru, which is 350,000 kg per sq cm. More recently P. Bernard measured 66,000 to 190,000 kg per sq cm for schists, 250,000 to 455,000 for quartzites, and only 2,000 to 26,000 for sandstones.

Apart from the very considerable differences between the values for a hard homogeneous rock like granite (Urseren) and a good compact sandstone (Rossens), the importance of the direction of measurement relative to the strata is obvious. It can be assumed that the lower value of E (measured normal to the strata) is attributable to the plastic deformation of the fissures, which first have to be closed before elastic deformation becomes possible.

If a cycle of loading, ranging from zero to maximum, is repeated several times, then the plastic deformation can be separated from the elastic rock deformation.

Grouting of the fissured rock definitely improves the modulus E. Oberti found that for a pressure p between 8 and 15 kg per sq cm, E varied from 35,000 to 52,000 kg per sq cm before and after grouting.

Quite independently, Bernard made further similar tests, measuring the strains in tunnel linings during and after injection and determining the stresses before and after grouting. His tests showed that the lining contracts during the grouting process (to a great extent permanently) ; the stresses under loading are reduced and are equalized in the various planes ; the deformation measured in the earlier tests were almost eliminated by the grouting.

Tests in schists were carried out with grouting pressures of 30 kg per sq cm (absorbing about 175 kg of cement per square metre) with the results that the modulus of elasticity was improved from 40,000 to 100,000 or even 236,000 kg per sq cm. It is likely that grouting is efficient in hard fissured rock, where the fissures are closed by the grout. Tests in sandstone and marl were attended by little success.

It should be recognised that the results of this last series of tests are of the greatest importance, and it is highly desirable that they should be repeated in all types of rock. The effect of pressure-grouting in decreasing the ratio E to the rock plasticity E′ should be further investigated.

Natural Pre-stressing of the Rock

It is apparent that the rock inside the mountain is stressed by its own weight before any excavation has been made. It is apparent also that this natural stressing or pre-stressing of the rock increases with the depth. At the beginning of the twentieth century, the Swiss geologist Heim expanded this theory by adding that, at great depths, the stress at any point must be the same in all directions. This is the hypothesis of the so-called ' hydrostatic ' stress distribution in the rock. A certain amount of backing was given to these theories by the rock behaviour in deep trans-alpine tunnels (Gothard, Simplon, Lotchberg, etc.) and in deep mines.

Measurements have recently been made inside deep tunnels and galleries with the result that Heim's theory has been approximately verified, and other theories must be discarded. However, more specific confirmation will be required if the theory is to become more generally accepted by designers.

The measurements will have to be made inside the tunnels as they are being blasted out. If it is to be assumed that, before blasting, the rock pressure is uniformly and hydrostatically distributed, the cutting of the tunnel disturbs this pressure distribution. The pressure in a direction normal to the tunnel periphery is released and the corresponding circumferential pressure near the tunnel, measured along a prolonged horizontal

[9] *Ch. Jaeger. ' Modern trends in arch dam construction and design.' Civil Engineering and Public Works Review, April Sept. 1950. and English Electric Journal, Sept. 1951, Vol. 12, No. 4, p.3.*

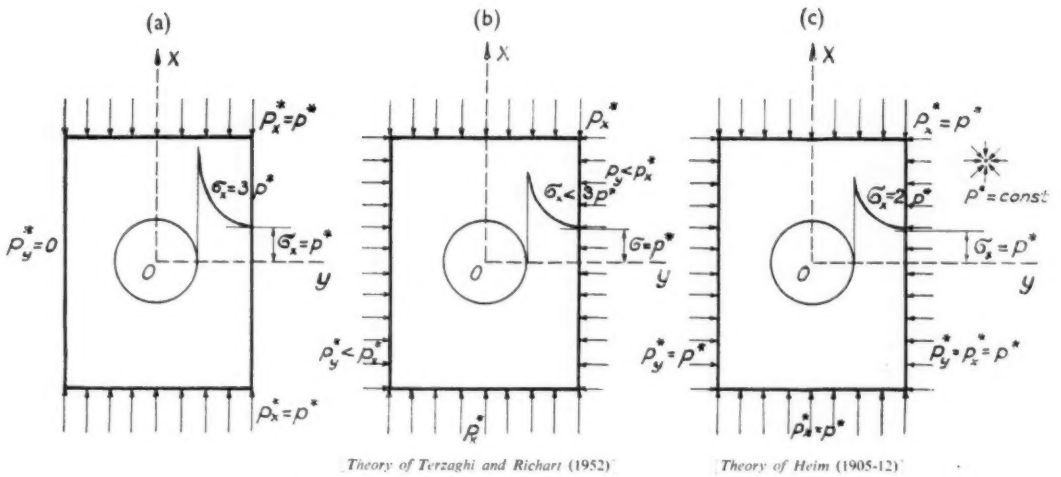


Fig. 10.—Stresses in the rock around an empty gallery

(a) The rock pressure p is parallel to direction Ox (b) the rock pressure $p_y < p_x^*$ (c) the rock pressure $p^* = p_x^* = p_y^*$ is 'hydrostatic'*

diameter, will be increased—perhaps doubled. So the pressure measured along the tunnel wall may not be the actual rock pressure in the undisturbed state.

If the rock, before blasting, was in plastic equilibrium and completely constrained, it begins to creep when pressures are released by the blasting. This creep may be slow, but there are indications that very brisk displacement may follow the instantaneous release of pressure. Several methods have been used for measuring the natural pre-stressing of the rock.

Behaviour of Rock round a Cylindrical Hole or Gallery

It has already been mentioned that drilling a hole or blasting a tunnel profoundly disturbs the pressure distribution in the rock.

Several authors have analysed the behaviour of the rock round a cylindrical tunnel while there was no internal pressure (p=0) in the tunnel. If the rock pressure p* produced by the rock's own weight is acting on the circular contour of the tunnel in one direction (vertical) only, the stresses at the tunnel wall on the horizontal axis Oy are, according to Timoshenko : $\sigma_r = 0$; $\sigma_t = 3p^*$ (see Fig. 10a).

In addition, the theory shows that on a diameter parallel to the pressure p* (vertical diameter) the stresses are tensile: $\sigma_t = -p^*$. Strains should be observed at the soffit of tunnels if the picture given by the theory were true, and tunnels filled with water at pressure p, causing an additional circumferential stress −p, would leak.

The recent theory of Terzaghi and Richart, introducing a component in a direction normal to p* (due to Poisson's ratio), shows that the stresses are (Fig. 10b) :—

$\sigma_t < 3p^*$ on a horizontal diameter.

$\sigma_t > -p^*$ on a vertical diameter.

If the pressure p* has the character of a hydrostatic pressure ($p_x = p_y = p^*$) (Heim), the stresses on the axis Oy are, as shown in Fig. 10c : $\sigma_r = 0$; $\sigma_t = 2p^*$ for any diameter.

The following remarks are based on the assumption that the theory of Heim is true and that the initial pressure distribution in the rock is of the so-called hydrostatic type, which causes the pressure at the border of the tunnel to be doubled ($\sigma_t = 2p^*$) after excavation of the tunnel. Denoting the limit of elasticity of the rock by σ_{el} and its crushing strength by σ_{cr}, then, if $\sigma_{el} > \sigma_t = 2p^*$, the tunnel is stable. If the local pressure σ_t is greater than the limit of elasticity, plastic deformation of

the rock will occur. Experience shows that although the plastic deformation of the rock is very slow, when once begun it is difficult to stop ; usually it continues until either the plastic deformation has evened out the stress distribution or the rock is completely crushed and the gallery collapses.

Crushing of the rock will certainly occur if $\sigma_{max} - \sigma_{min} > \sigma_{cr}$. Fig. 11 (a, b and c) represents, according to Talobre, the probable distribution of pressure for

$\sigma_t = 2p^* < \sigma_{cl}$; $\sigma_t > \sigma_{cl}$; $\sigma_{max} - \sigma_{min} > \sigma_{cr}$

respectively. It should be clearly understood that these three sketches give only qualitative information, for they cannot take into account the lack of homogeneity of natural rock.

In the case where the distribution of pressure is determined by the gravitational field alone (Fig. 10a), the stress distribution can be ascertained by model experiments. Tests made for the Krangede tailrace tunnel (Sweden) showed an ogive cross-section to be more favourable than a circular one.

Rock Stability adjacent to a Pressure Conduit

The hydrostatic pressure inside a conduit, gallery or tunnel filled with water is $p = wH$, where H denotes the head and w the specific gravity of the water. If $p = p^*$ the conditions round the perimeter of the gallery would be identical to those prevailing before the construction of the tunnel, and the rock would revert to the original state of uniform stress distribution $p^* =$ a constant (if the rock is assumed to be homogeneous and the overburden deep). It is easy to check that the stress conditions along the perimeter of the gallery then give $p = \sigma_r = -\sigma_t = p^*$, which, added to the stress shown in Fig. 10c ($\sigma_r = 0$ and $\sigma_t = 2p^*$), finally yield $\sigma_r = \sigma_t = p^*$ everywhere.

A deep tunnel in sound homogeneous rock with internal water pressure $p = p^*$ would be perfectly safe without any lining, whatever the value of p^*. But rock is rarely sound and homogeneous, and hydro-electric power tunnels and shafts are rarely deep. For these and other reasons the water pressure p should be less than p^* and it is convenient to write $p = p^*/n$, where n has the significance of a safety factor. When using the rule-of-thumb that the water pressure p inside the tunnel should not be more than half the depth of the overburden ($p = \frac{1}{2}H$), the safety factor n is equal to twice the specific density of the rock, $w = 2{\cdot}5$. This gives $n = 5$, which seems to be a reasonable safety margin to adopt when considering the safety factors usually applied to steel and concrete. Some tunnels have recently been designed on far bolder assumptions with reduced values of n. An approximate estimate of the redistribution of the stresses in the rock after introduction of the water pressure p in the gallery will be obtained by superposing the stress distribution as shown in Fig. 8 on that represented in Fig. 11. These comments summarize the modern views on pressure shaft theory.

Outside Water Pressure and Danger of Buckling of the Steel

It should be emphasized that no rock or concrete is completely impervious. Hydrostatic pressure may be transmitted long distances through small rock fissures or through the pores of the concrete. It must, therefore, be assumed that since the concrete lining of galleries and shafts is somewhere in direct contact with water (for example, with the

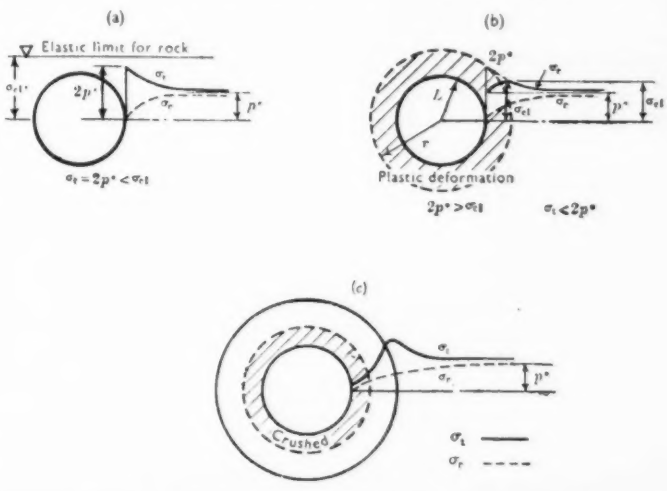


Fig. 11.—Stresses in the rock round an empty tunnel (after Talobre and others)

water in the surge tank), full hydrostatic pressure may be operating behind the steel lining.

At the present time, most designers agree that the external water pressure is a major problem, but opinions diverge considerably regarding the distribution of the external pressure and even more so regarding the methods for stiffening the steel lining and the design of the lining against buckling.

Some designers claim that any reinforcing rib or anchorage of the steel lining would make it impossible to ensure a perfect concrete filling behind the plate linings, so they suppress all forms of anchorage. A typical modern example is the pressure shaft of the Gondo power station where the pipes are not anchored in the concrete and had to be reinforced internally during the concreting process to withstand the pressure of the wet concrete. The shaft was finally grouted at low pressure.

There are many modern examples of the opposite technique, in which the plate linings are solidly anchored to the concrete. It is a matter of detailed design to shape the anchorages so that they do not hamper the dense packing of the concrete lining. The grout holes need to be so arranged that grout pressure will penetrate to every point where voids might have been formed during the initial concreting.

Table VI gives some details of the reinforcing hoops or ribs which were adopted at Isère-Arc, Oberaar, and elsewhere. Proposals were made to replace the conventional angle-irons by other types of hoop, or by arranging the plates differently (Isère-Arc). Electricité de France are now introducing the so-called ' hedgehog spine ' anchorage, which consists of studs welded to the plate ; one of the first examples is the steel lining of the Rossens intake and discharge tunnels, where the studs were welded by hand. Electricité de France propose to introduce stud-welding machines to lower the cost of anchoring.

Grouting

The problems of natural pre-stressing of rock and of rock grouting have been dealt with at full length in a paper by the author[10].

The importance of grouting for redistributing the stresses in the rock and for applying compression

[10] *Charles Jaeger. ' Present trends in the design of pressure tunnels and shafts for underground hydro-electric power stations '. Paper No. 5978, Institution of Civil Engineers, read November 1954 ; Part I Proc. March 1955.*

TABLE VI

THICKNESS OF CONCRETE PACKING, LENGTH OF PIPES, AND DESCRIPTION OF ANCHORAGES FROM STEEL TO CONCRETE

Pressure shaft	Thickness of concrete		Length of pipes		Anchorages
	m	in	m	ft	
Innertkirchen	?	?	10–12*	33–39	None
Handeck II†	0·06	2·33	?	?	None
Oberaar†	0·10–0·13	4–5	10	33	60/20 to 80/25-mm angles. Six on a length of 10 m.
Verbano	0·15	6	10	33	—
Gondo	0·2–0·35	8–14	8–12‡	26–39	None
Isère-Arc	0·40	16	3	10	100/100/10 to 120/120/12-mm angles. Two hoops per 3 m.
Kemano§	0·6	24	2×4·3 or 2×8·6 welded	2×14 or 2×28 together	Prepakt concrete, 1–3 in. placed by 10 in. pipe.
Proposed by Mr. Talobre for new designs ..	0·25	10	—	—	Hedgehog spine.

* *Owing to insufficient rock overburden, the distribution pipes of Innertkirchen are enclosed in a second pipe, which has a wall thickness of 20 mm, the clearance between the pipes being 20–40 cm.*

† *Concreting pipes were used. (The concrete for Gondo was a rich mix, with 275 kilograms of Portland cement and 50 kilograms of pozzolanic cement per cubic metre of concrete. An air entraining agent was also added.)*

‡ *On the horizontal section the pipe length was restricted to 8 metres because of limitations on the weight of sections of pipe.*

§ *" Prepakt " concrete, aggregates 1–3 inches, placed 10-inch pipe. Two lengths of pipe were welded together and the assembled sections then brought to the inclined shaft.*

to the concrete lining and to the steel shell, thus creating radial and tangential stresses, has been realized only very recently. The effect of grouting on the rock elasticity has been shown in recent years.

The obvious danger of inadequate concrete backing to the lining should be countered by systematic grouting between the steel lining and the concrete, the grouting holes being concentrated along the steel reinforcement ribs and between the concrete and rock. It is also suggested that grouting increases the stability of the steel lining against buckling.

The technique of grouting was developed with the intention of suppressing water leakage through the rock when no steel lining was provided, as well as to stop the ground-water pressure penetrating to the steel shell.

Systematic rock grouting was used in 1940 for the 10-km-long pressure tunnel at Innertkirchen, in order to pre-stress, in compression, the thin pre-cast curved asbestos-cement plates with which the tunnel is lined. This is probably one of the first examples of pre-stressing being used for a tunnel on such a large scale.

Since then several designers have proposed ways to facilitate grouting procedure. Kieser in Austria has patented procedures in which pre-cast concrete blocks replace the ordinary concrete lining. They are masoned against a rough concrete lining covering the rock surface. The pre-cast blocks are provided with a small circular groove running along the outside of the concrete lining. Grout is forced into these grooves, compressing the cylinder formed by the pre-cast blocks. The consequent pre-stressing should be greater than the stress created by the water pressure p inside the pressure tunnel.

Data on Large Pressure Shafts

Data on large pressure shafts have been summarized in Tables II, III and IV. Table II, part of which is from a publication by Talobre, gives general data on existing large steel-lined shafts. Table IV compares the calculated stresses in the steel linings at the base of the shafts, assuming that no load is transmitted to the rock. These calculations are based on the data available from many publications. Table III refers to the maximum power concentrated in single large shafts.

The information contained in these three tables is self-explanatory and illustrates the scope of modern projects better than any comment.

V. TUNNELLING METHODS AND THE EXCAVATION OF THE LARGE CAVERNS FOR MACHINE HALLS

Progress in Methods

To understand the rapid development of the new technique of underground power stations it is necessary to appreciate the considerable progress achieved in tunnelling methods. The progress consists mainly in extensive mechanisation of the drilling and of the removal of spoil, and in the use of high-speed drilling equipment, finally resulting in rapid progress and lower cost per cubic foot of excavation. On the other hand, considerable progress has been achieved in dealing with difficult rock conditions. Finally the methods for concrete lining the tunnels have also been considerably improved.

Recently Italian engineers published reports on a hydro-power tunnel where conventional methods having been used at the beginning, the contractors switched over to modern methods, so that speed, progress and costs could be compared. The Swiss also compared American and Swedish practice and equipment from the double point of view of speed and cost. The French used highly mechanized tunnelling at Tignes and Isère-Arc, and work in Scottish tunnels has been widely publicised and commented upon in Great Britain. Finally, direct information from Swedish sources is available.

The ' jumbos ' supporting the drilling equipment, and the shovels and trucks used for removal of the spoil, have been described in many papers : so have the Americans' heavy drills (Ingersoll Rand) and the Swedish light drills (Atlas-Diesel or Atlas-Copco)[11]. In Table I the records obtained at Kemano are listed. The relative efficiency of the American and the Swedish equipment can best be

[11] *The Engineering Journal, Montreal, Vol. 37, No. 11, Nov. 1954.*

discussed on the basis of recent publications by 'Water Power'[12]. From these on Kemano, and other sources, the following comparative data can be extracted, which is best summarised in tabular form (Table VII).

TABLE VII

COMPARATIVE DATA ON THE HEAVY DRILL AND LIGHT DRILL PERFORMANCES AT KEMANO

	Light-weight drills	Heavy-weight drills
Heading	West Tahtsa	Kemano
Rock	Metamorphic complex	Quartzite diorite
Maker	Atlas-Copco	Ingersoll-Rand
Number of rock drills..	16—21	15
Typical shift crew ..	21—31	34—40
Bits steel	Coromant integral rods	Carset detachable bits
Footage per bit ..	600	240
Number of regrinds ..	8—10	8—10
Drilling time in minutes	87—105	100—105
Rate of penetration per rock drill (in. per min.)	9·6	9·64
Rate of penetration per man (in. per min.) ..	6·98	4·67
Footage drilled per round	1,100	1,148
Footage per shift ..	12	12
Pounds of powder per cu. yard	3·2	5·41

The advantage of high efficiency drilling methods is now universally accepted.

The lighter equipment used at West Tahtsa shows marked economies in this table : the Coromants apparently out-drilled Carset bits by more than two to one. However, some allowance should be made for the rock. Powder consumption, partially due possibly to the small holes drilled because of the smaller diameter of coromant steels which were used with the light drills, was 41 per cent lower at the West Tahtsa heading. Experience on the Alcan project and on many Swedish projects would seem to show that the light-weight steels and small-diameter holes are more than adequate for any type of tunnelling work.

As 22½ per cent less men were employed at West Tahtsa per heading, a considerable saving resulted in ancillary services needed to supply the camp personnel in this remote area.

A similar advance of modern technique for tunnelling in rock of mediocre quality can be mentioned. The 'roof bolting' has proved a success on many jobs in faulty rock[13]. The method, if rightly applied, is efficient and cheap.

Spectacular results can be obtained in difficult rock, where pressure and even rock displacements are noticeable. One interesting example of the difficulties encountered is the downstream section of the 8-mile-long tunnel of Malgovert, which has been amply described in several technical papers.[14] There, steel props were used over long stretches of tunnel. Where they were found to be insufficient, they were replaced by complete reinforcement rings in reinforced concrete.

The greatest difficulty was encountered at adit No. 13. When driving the pilot tunnel in the upstream direction, a zone of broken quartzite was encountered, causing fine granular material and water to run into the tunnel at 130 m from the entrance. Work had to be given up several times until the dangerous passage was eventually grouted with silica grouting forced into the fissures under 8 atmospheres pressure, behind a concrete retaining wall of 1·50 m thickness, over about 35 m length at a time. About 110 m of tunnel were grouted with this method, when tunnelling was proceeding with the utmost care.

This definite progress in the tunnelling techniques has also its bearing on the excavation of large caverns for machine halls. The bolting of rock or the anchoring of large pieces of rock with pre-stressed cables are techniques which are being used more often. Anchorages with pre-stressed cables can also be used for preventing future rock creep and plastic rock deformations.

Excavation for Machine Halls

Light drills have been successfully applied to cavern excavation, and in one recent case (Kemano machine hall) diamond drilling has been used in conjunction with rock blasting.

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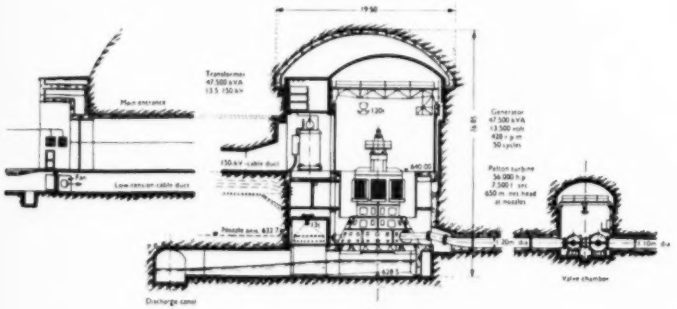
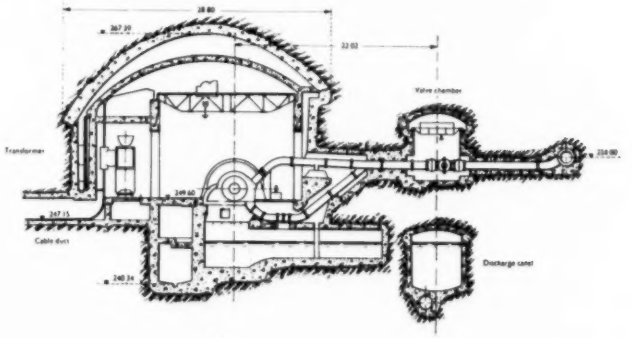
[12] *'Tunnelling operations on the Alcan Project', Water Power, Vol. 6, No. 5, May 1954.*
'Kitimat'. Water Power, Vol. 6, Nos. 3 and 4, March and April 1954.

[13] *Lu. Rabcewicz, 'The Forcacaba Hydro-Electric Scheme.' Water Power, Vol. 5, Nos. 9, 10 and 11, Sept. Oct. Nov. 1953.*

[14] *Ch. Jaeger. 'The Malgovert tunnel'. Water Power, Vol. 4, No. 7, July 1952.*
J. Pelletier. 'The Construction of Tignes Dam and Malgovert Tunnel', Institution of Civil Engineers, Works Construction Paper No. 26, Proceedings, Part III 1953.



(a)



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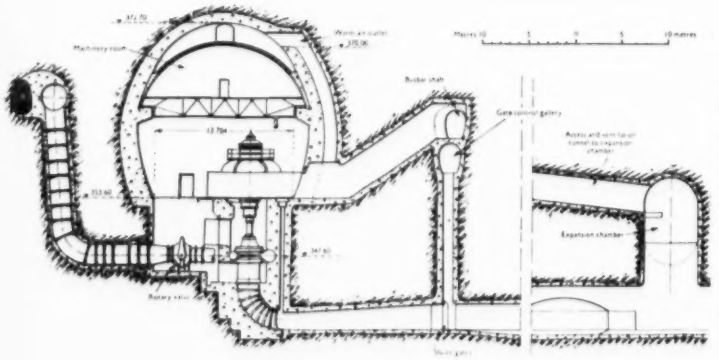

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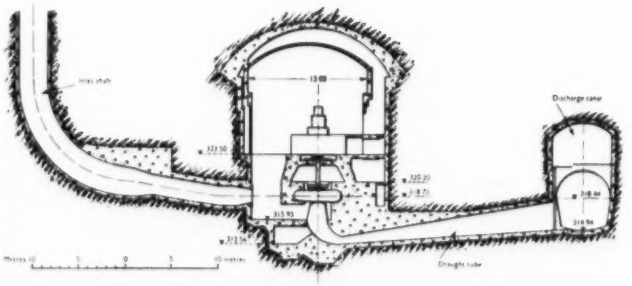


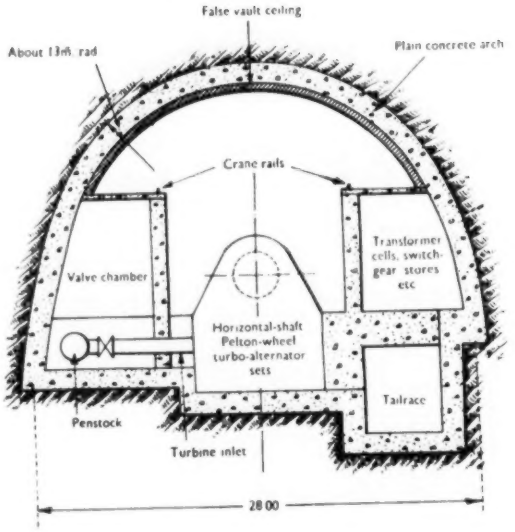
(d)

Fig. 12a.—*Innertkirchen, Switzerland* (*gross static head* 672 *metres*)

Fig. 12b.—*Santa Massenza, Italy* (*gross static head* 590/460 *metres*)

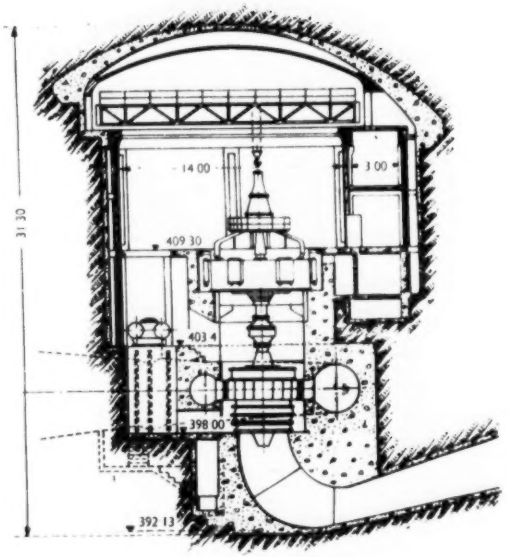
Fig. 12c.—*Santa Giustina, Italy* (*gross static head* 183/95 *metres*)

Fig. 12d.—*Isère-Arc, France* (*gross static head* 152 *metres*)



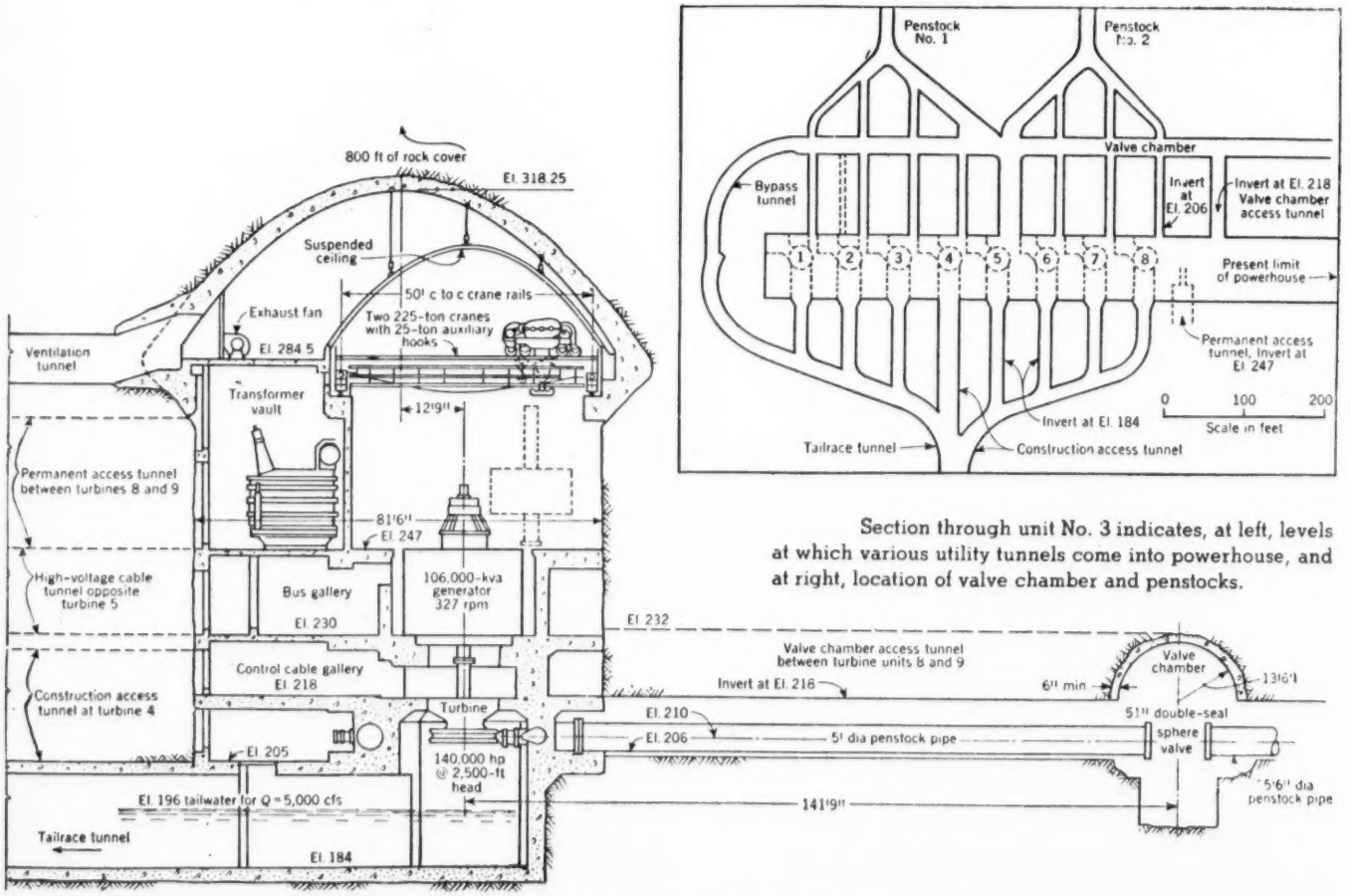
(e)

Fig. 12e.—*Peccia, Switzerland* (*gross static head* 426 *metres*)



(f)

Fig. 12f.—*Lavey, Switzerland* (*gross static head* 40,6 *metres*)



Section through unit No. 3 indicates, at left, levels at which various utility tunnels come into powerhouse, and at right, location of valve chamber and penstocks.

Fig. 13.—Kemano, Canada (gross static head 790 metres)

(Illustration by courtesy of 'Civil Engineering' U.S.A. Originally published in articles by W. G. Huber on the Alcan British Columbia Hydro Project, February and June, 1953.)

The dimensions of underground power houses depend on the size and number of generating sets and the station arrangement. The turbines may be impulse wheels (Pelton) or reaction wheels (Francis or Kaplan) and of vertical or horizontal type. The basis upon which rests the choice between the different types of turbines is essentially the same as for ordinary above-ground stations, but increased importance is attached to the volume of rock excavation. The vertical Francis turbine often requires less excavation for the valves and distribution pipes. The tendency in the near future will obviously be towards compact design of the generating sets, and rearrangement of the machine hall floors. The volume of additional excavation required by the travelling crane and the space required for dismantling the sets and lifting the rotor are troublesome to designers, but no easy alternative will be found to the conventional arrangement.

The transformers are sometimes arranged inside the same general excavation as the generating sets, as at Innertkirchen and Isère-Arc. They can also be located in a separate excavation parallel to the main excavation as at Vinstra and Soverzene, or nearby as at Harspranget. The final possibility is an above-ground location as at Krangede. A simple rule used by Italian engineers is that if the length of the low-voltage transmission cables is more than 250 to 300 metres, the arrangement with underground transformers is cheaper. Norwegian designers seem to favour placing the transformers underground, partly for military reasons.

The valves upstream of the turbines can be located inside the main excavation or in a special excavation upstream of the general turbine room. This last arrangement is mostly retained for high-head schemes. For a small head there will be a tendency to suppress these valves and rely on the cheaper intake valves.

The technique of excavating the power house will depend on the rock, its stability and strength, and the main direction of the strata, and on the amount of water to be expected, the cost of excavation and the constructional equipment the contractor is prepared to use on the job. Italian contractors, using relatively cheap labour, will adopt different techniques than Swedish or American contractors. But there is a definite tendency in countries like France, Switzerland or even Italy for contractors to adopt Swedish or American plant and methods.

Normally the excavation and the concreting of the arched roof of the power house will be given first priority and then the excavation work will proceed downwards on the whole width of the power house, as at Lavey, or in trenches along the walls, leaving a central core to be excavated later as at Innertkirchen. An entirely new technique has been used at Kemano.

The power house walls will usually be lined with

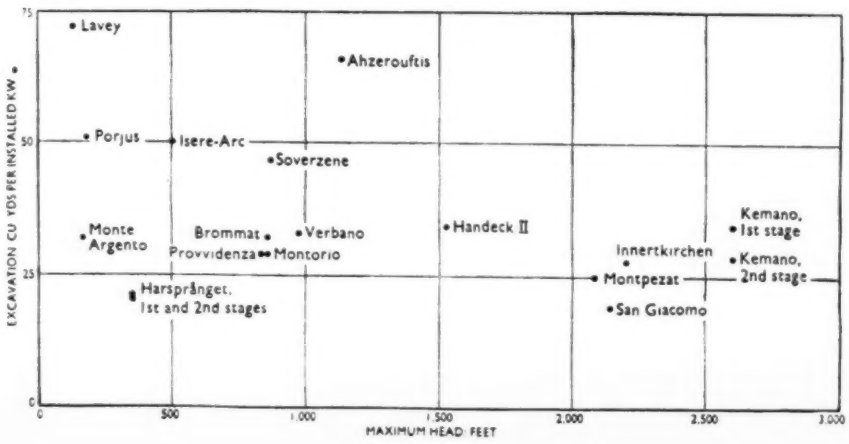


Fig. 14.—Relation between volume of excavation and gross head

TABLE VIII

DATA ON UNDERGROUND POWER HOUSES

Date of commission	Power station	Country	Capacity : kW	Gross head : ft	Turbines : h = horizontal v = vertical	Volume : cu yds	Excav. for transf. or valve house, etc. : cu yds	Volume of power house per kW installed : cu yds
1910	Porjus	Sweden	60,000	183	8 Francis, h	35,000	6,000	0·58
1932	Brommat	France	186,000	855	6 Francis, v	60,000	16,000	0·32
1942	Innertkirchen	Switzerland	210,000	2,200	5 Pelton, v	59,000	20,000	0·28
1947	Lumiei (Ampezzo)	Italy	58,500	1,465	3 Pelton, h	33,000	—	0·565
1948	San Giacomo	Italy	200,000	2,140	3 double Pelton, h	37,000	5,000	0·19
1948	Soverzene	Italy	220,000	870	4 Francis, v	85,500(*a*)	16,500(*a*)	0·390(*a*)
						102,000(*b*)		0·465(*b*)
1949	Mar	Norway	180,000	—	—	60,000	—	0·334
?	Vinstra	Norway	180,000		Francis, v	30,000	8,170	0·167
1949	Provvidenza	Italy	150,000	838	3 Francis, h	44,000	3,000	0·29
1950	Lavey	Switzerland	76,000	133·5	3 Kaplan, v	54,500	7,200	0·715
1952	Handeck II	Switzerland	114,000	1,520	4 Pelton, v	39,000	—	0·34
1951	Santa Giustina	Italy	108,000	560	3 Francis, v	40,000	—	0·37
1951	Harspranget	Sweden	288,000(*c*)	353	3 Francis, v	63,300	30,000(*e*)	0·22(*c*)
			380,000(*d*)		4 Francis, v	79,000		0·206(*d*)
1951	Ahrzerouftis	Algeria	66,500	1,125	Two 40,000 h.p. Pelton, v	44,000(*f*)	—	0·66
					One 7,500 h.p. Francis, v	80,000(*g*)	—	1·20
1951	Santa Massenza I	Italy	302,000	1,940 to	6 Pelton, h	203,000	10,900(*h*)	0·92
	Santa Massenza II	Italy	25,500	1,505	2 Francis, v			
1952	Monte Argenta	Italy	66,000	164	3 Francis, v	21,000	8,000	0·32
?	Montorio	Italy	100,000	845	3 Francis, v	29,000	1,000	0·29
1952	Verbano	Switzerland	100,000	973	4 Francis, v	33,000	—	0·33
1953	Isère-Arc	France	135,000	500	4 Francis, v	68,000	—	0·50
1954	Montpezat	France	116,000	2,080	2 double overhang Pelton, v	26,300	—	0·226
1954	Kemano	Canada	835,000(*j*)	2,597	8 Pelton, v	278,000	21,000	0·333
			1,670,000(*k*)		16 Pelton, v	473,000	—	0·284
1953-4	Nilo Pecanha	Brazil	355,000	1,122	6 Francis, v	98,000	—	0·28
1955	Ceannacroc	Scotland	20,000	299	1 Francis, v	9,800	—	0·49
1957	Glen Moriston	Scotland	30,000	311	2 Francis, v	12,700	—	0·40
Constr.	Cubatao	Brazil	465,000	2,365	6 Francis, v	123,000	7,900	0·29
Constr.	Fionnay	Switzerland	127,500	1,555	3 Francis, v	27,000	1,800(*a*)	0·21(*a*)

NOTES. (*a*) *Without transformer house.* (*b*) *Including transformer house.* (*c*) *First stage.* (*d*) *Second stage.* (*e*) *For transformer house.* (*f*) *Useful excavation.* (*g*) *Including 10-foot thick walls and roof.* (*h*) *For valve house.* (*j*) *First stage.* (*k*) *Second stage.*

concrete, the concrete adhering directly to the rock. Norwegian engineers prefer to leave the rock without direct lining, the walls and the roof being at some distance (0·50 to 1·0m) from the rock. Thorough ventilation is necessary to keep the rock dry. This technique has also been used in countries other than Norway and Sweden, e.g. Lavey in Switzerland. In solid granite the walls may be without any linings, and the bare rock is directly visible as at Hojum, Sweden. Westerberg mentions one case where the arched concrete roof has been suppressed altogether, the rock being covered with expanded metal and a gunited mortar lining. Norwegian engineers favour designs where the concreted arched roof with or without ribs is at some distance from the rock roof. They claim that they have had no damage whatsoever due to falling rock.

A rule-of-thumb given by Norwegian engineers proposes that the overburden above any power house excavation should be twice the width of the excavation, with a minimum overburden of 30 to 35 ft. Cases are known, e.g. at Clachan in Scotland, where the power house was excavated by the trench and cover method. There this method was cheaper than a conventional power house design above the ground level. For large power stations

where the strata of the rock is suitable, the longitudinal axis of the power house should be at an angle of 20° to 30° to the axis of the pressure shaft, since this arrangement is favourable for the design of the distribution pipes.

When water is expected along the walls, the wall may be made double with a drainage in between. If rock pressure is expected to develop, specially reinforced walls are indispensable for the stability of the excavation.

The walls of the power house at Lumiei are arched in the horizontal direction and constitute segments of cylinders with a vertical axis. Against

TABLE IX

DIMENSIONS OF SOME LARGE UNDERGROUND POWER STATIONS

Power house	Head: metres	Total height*: m	Total width: m	Total length: m	Crane span: m	Crane capacity: tons	Turbine horse-power	Distance between turbine centres: m	Position of transformers	Valves
Kemano, 1st stage	790	41	25·5	214	—	2 × 225	8 × 140,000	—	Inside main excavation	Special excavation
Kemano, 2nd stage		42·4	24·8	344	15·25	—	16 × 140,000	18·3	Inside main excavation	Special excavation
Innertkirchen..	672	26·85	19·5	96·70	10·8	120	5 × 56,000	14·50	Inside main excavation	Special excavation (28-ton crane)
Montpezat ..	634	23·2	16·1	50	13·5	2 × 135	2 × 81,000	—	Outside	?
Santa Massenza I and II	590/460	28·0	28·8	192·7	14·2	—	4 × 80,000 2 × 40,000 1 × 25,000	18·0	Inside main excavation	Special excavation
Cavergno (Maggia)	590	21·5	28	—	11·6	—	2 × 27,500	—	Inside main excavation	Inside main excavation
Lumiei	480·6	24·2	15·4	71	12·0	—	3 × 25,500	—	Outside	Special excavation upstream of main excavation
Handeck II ..	463	25·55	16·8	79·25	10·70	—	4 × 41,000	14·0	Inside main excavation	Special excavation
Peccia (Maggia)	426	21·5	28	—	11·6	—	2 × 23,500 2 × 11,600	—	Inside main excavation	Inside main excavation
Ahrzerouftis I and II	345	22·4	20	67	—	120	2 × 40,000 1 × 7,500	—	Outside	
Vinstra	?	27	13	73	11	—	4 × 60,000	11	Inside special excavation	
Bersimis ..	336	28·5	19·4	171	18·4	2 × 200	8 × 175,000 8 × 200,000	16·8	Inside main excavation	Straight flow valves, inside
Snowy Mountain T1	334	28	17	92	14·5	—	4 × 134,500	12·8	Inside special excavation	Straight flow valves, inside
Soverzene ..	265	35·1	25·5	73	17	—	4 × 72,500	14	Inside special excavation	Inside main excavation
Brommat ..	260	31·4	21·8	?	11·5	140	6 × 40,000	—	Outside	Inside main excavation
Santa Giustina	183/95	29·5	17	61·3	13·7	—	3 × 47,500	12·8	Outside	Inside main excavation
Isère-Arc ..	152	31·6	16·8	56·25 109†	13	—	4 × 45,000	10	Inside prolonged main excavation	Inside main excavation
Harspranget, 1st stage	108	33 43‡	183	100		2 cranes	4 × 127,000	20	Inside special excavation	—
Lavey	40·6	31	21	64	14·5	2 × 60	3 × 33,500	14	Outside	Separate excavation

* *Not including draught-tube height.* † *Including transformers and workshop.* ‡ *Including draught-tube height.*

higher pressure of rock, a cylindrical roof and walls of elliptic cross-section are favoured. In the well-known power house of Santa Giustina the elliptic cross-section is reinforced by the heavily reinforced generator floor, acting as a horizontal strut against the horizontal component of the rock pressure.

The designers of the power house of L'Ahrze-rouftis thought that a semi-circular roof and thick, slanting, lateral walls would provide for additional safety. The French designers estimate that for the worst possible conditions of pressure, the stresses in the arched roof are not more than 65 kg/cm^2 and 93·8 kg/cm^2 in the lateral walls.

Fig. 12 (a-f) shows sketches of the principal designs which have been evolved. They compare with the impressive power house of Kemano (Fig. 13). Tables VIII and IX summarize the main data of several well-known installations. Fig. 14 shows the relation between the volume of excavation and the gross head for a number of underground power houses.

There is a tendency when designing underground power houses to choose the station arrangement giving the minimum excavation. The generator support and the spiral casings are developed along the conventional lines adopted for above-ground stations. Isère-Arc shows one interesting alternative. The conventional cylindrical generator supports for the vertical Francis turbines are replaced by semi-spherical cupolas, whose diameter is greater than that of the spiral casings. The turbine erection began when the civil contractor had built the cupola, so that civil engineering and turbine erection did not interfere with each other.

Vertical access shafts were favoured some years ago, but to-day contractors prefer longer inclined tunnels which can be used by diesel-engined trucks and heavy lorries.

Mainardis, Heggstad and others have emphasised the importance of the electro-mechanical equipment required for underground stations, such as the type of generator, cooling system and ventilation to be adopted, and advantages of having the transformers underground or over ground.

Space here permits only a brief reference to the problem of the cost of underground power stations. Lewin, basing his findings on figures of Swedish extraction and on some American data, thinks that underground stations may be up to 30 per cent cheaper than conventional designs. Even if some corrective information from Sweden is being considered, there will be in any case a substantial margin in favour of underground stations. Many consulting engineers will confirm these results but will also be able to indicate other alternatives which may cost less than underground designs. There is no universal rule, and well-informed specialists know that there are exceptions. A design with a power house at the toe of the dam may be cheaper than an underground station if the flood water can be spilled over or released without too much interference with the hydro-power aspect.

Summarizing all the available information from many countries, there is considerable evidence that underground stations tend to be the less expensive, and when such a design is possible or commendable technically it should be considered for cost comparison with more conventional above-ground solutions.

One point of great importance must be underlined which will give the conclusion to this survey. The future will favour great concentration of energy production ; Harspranget, Donzère, Kemano, and some of the Russian designs are concentrating large masses of hydro-power. This concentration makes power comparatively cheap and facilitates the concentration of industry, a social and economical process similar to the earlier industrial concentration near the coal mines[15].

Underground stations are most suitable for this high concentration of power, and this is the last and determining argument for a greater joint effort in developing our knowledge of all the questions involved.

[15] *See Charles Jaeger, 'The Hydro Electric Industry', The English Electric Journal, Vol. 13, No. 8, December* 1954.

The Napier 'Eland' Aero Engine for the Fairey 'Rotodyne' Aircraft

THE NAPIER 'ELAND' propeller-turbine aero engine was described in the March 1955 issue of this journal (Vol. 14, No. 1, page 23). A derivation of this engine is now being employed as the power unit of the Fairey 'Rotodyne', and this large helicopter is scheduled to fly with Eland engines early in 1956.

Great interest is being shown in the Rotodyne in both military and civil aeronautical circles, and the aircraft's versatility and large load-carrying capacity should ensure its wide use in both fields of aviation.

Examples of loads the Rotodyne will accommodate illustrate the diversity of the helicopter's possible applications. Its large fuselage, rectangular in cross-section, will take 44 passengers and their baggage or 40 troops and equipment; a Continental touring coach and passengers, or a 'Jeep' and 25-pounder gun; 150 sheep or 11,000 lb of mail in sacks. Moreover, the cross-section of the fuselage could be altered—the head-room increased particularly—to take loads such as an Army 3-ton lorry.

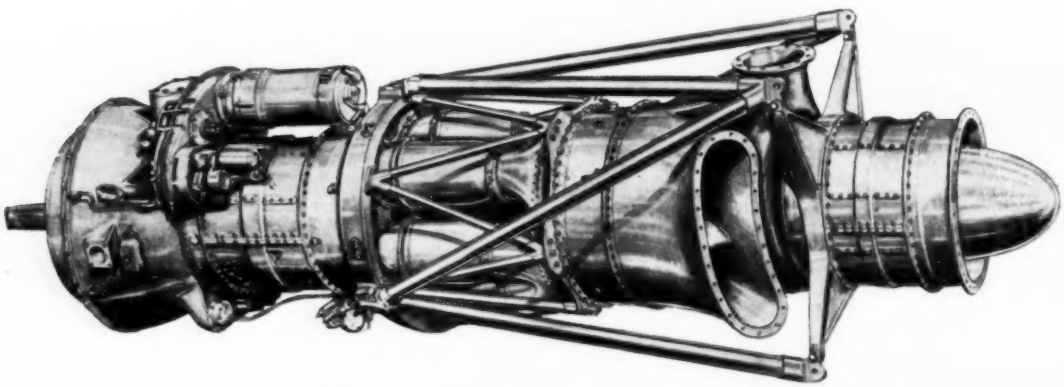
The two Elands are underslung on a short high wing, through which compressed air to the rotor tips is ducted. This arrangement allows the fuselage to be unobstructed and, with its large rear loading doors, the aircraft will be popular with operators.

The engine for the Fairey Rotodyne is basically similar to the standard Eland engine as fitted to orthodox fixed-wing aircraft.

To meet the requirements of the Rotodyne an auxiliary compressor is mounted co-axially at the rear of the engine and is supported by a tubular mounting which itself acts as the main engine mounting. A hydraulic coupling is mounted between the turbine and the auxiliary compressor in such a way that the power can be taken either through the propeller for forward flight or through the auxiliary compressor in the form of compressed air to the rotor for vertical flight.

The engine forward of the turbine is identical with the standard Eland engine, and therefore full advantage can be taken of experience gained with the standard engine both on the test bed and in the air. This has the further great advantage of facilitating production and maintenance.

The engine is at present rated at 3,000 e.h.p.



The Napier 'Eland' aero engine used as the power unit of the Fairey 'Rotodyne'

Short-Circuit Forces on Turbo-Alternator End-Windings

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This article is in all essentials a reproduction of the paper read by the authors before the Institution of Electrical Engineers in London on the 15th of December 1954, and published in the Proceedings of that Institution, Part A, April 1955.

THE PHENOMENAL ADVANCES in the output of individual turbo-alternators in recent years have presented the designer with increasingly difficult problems. Among these, although it is not insuperable, is the requirement of incorporating in the stator end-windings sufficient mechanical strength to withstand the forces which would occur if a solid short-circuit were applied at the generator terminals, at the same time providing adequate spacing between the coils for the passage of the cooling medium.

Thirty years ago a 20,000-kW generator was considered to be a large unit ; generating voltages were low, the sets often being in close proximity to their loads. Many large industrial consumers of electricity, such as factories and collieries, installed their own generating plant, the output from which was fed into long runs of open busbars. Faults in these circumstances were not uncommon, and a busbar flashover represented a short-circuit electrically close to the machine terminals. It was probably in the light of this type of operation that clause 36 was included in the relevant British Standard (B.S. 225 : 1925). This states that " Short-circuit tests, when required, shall be specified at the time of inviting tenders for the machine."

At that time it was reasonable to require an alternator to be subjected, on test, to a severe terminal short-circuit, since this was a likely operational contingency. Over a number of years the principle was thus established of applying 3-phase short-circuits from full voltage on those early and relatively small machines. These tests are not specifically required by B.S. 225, but the precedent having been set, manufacturers have felt bound to accede to continued requests for the application of full voltage short-circuits on machines of ever-increasing ratings.

The development of high-voltage transmission led to the interconnection of existing power stations and to the construction of new stations satisfactorily placed with respect to fuel supply and cooling-water facilities. Generation may now be carried out at some distance from the load centres, and large alternators, more often than not, are solidly connected to individual step-up transformers with relatively short runs of busbars on the low-voltage side. The likelihood of a fault at or near the machine terminals in these circumstances is therefore remote compared with the conditions obtaining when B.S. 225 was originally prepared.

Faults may occur fairly frequently on that part of the system connected to the high-voltage side of a generator transformer, but in such cases the fault-power and current from the generator are limited by the transformer impedance in addition to that of the alternator itself. In a typical case the peak initial current to a high-voltage fault might be reduced to half the value associated with a solid short-circuit at the machine terminals. Additional factors, referred to in Section V, reduce still further the currents to be expected in modern installations.

In what follows it is suggested that short-circuit tests from full voltage represent progressively more severe and less realistic conditions as the sizes of individual machines increase. The highest ratings of 2-pole alternators supplied for British power undertakings over the last 30 years are illustrated in Fig. 1. Alternators of more than 100 MW rating at 3,000 r.p.m. are now in the course of manufacture in this country and still larger units are being considered. Generators rated at 250 MW at 3,600 r.p.m. are at present under construction in

the United States, and machines of similar capacity will undoubtedly be made before long for connection to the British Grid.

The primary object of this article is to present the view that while some short-circuit tests are probably desirable as a check on alternator reactances and on general manufacturing standards, it is unnecessarily severe to apply such tests from 100% rated voltage.

1. SHORT-CIRCUIT FORCES

The particular aspect of alternator short-circuits with which this article is mainly concerned is that relating to the forces acting upon the stator conductors, and especially those on the stator end-windings. As is well-known, each one of a group of current-carrying conductors experiences electromagnetic forces whose magnitude and direction depend upon the configuration of the conductors and the amplitude and phase of the currents. The instantaneous force on any small element of conductor is given by

$$F = 0{\cdot}57IB \sin \theta ds \times 10^{-6} \text{ lb.} \quad . \quad . \quad (1)$$

where I = Current through the element, amp.
B = Magnetic flux density at that point, gauss.
θ = Angle between I and B.
and ds = Length of the element, in.

The direction of the force F is mutually perpendicular to the directions of I and B. If the circuits are in air, B is directly proportional to the magnetizing force and therefore to the currents flowing in the configuration ; the mechanical forces are then functions of current products.

Forces on Stator Conductors

In a turbo-alternator having a subtransient reactance of 10%, the initial current following a 3-phase short-circuit from no-load, rated voltage, is ten times the full-load current. If maximum asymmetry occurs in one phase and decrement is neglected, a peak current will flow having a magnitude 20 times the peak value of full-load current. The peak forces associated with the conductors of that phase will therefore reach values of 400 times normal. The stator forces depend on many design features but in particular cases may increase more than in proportion to the output. The ratings of individual generators shown in Fig. 1 indicate that the short-circuit forces on the windings of present-day machines may be appreciably greater than those on the largest manufactured 30 years ago.

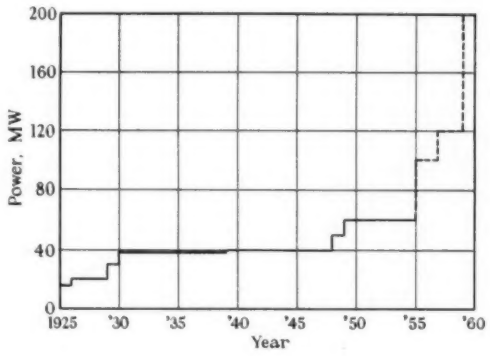

Fig. 1.—Ratings of 2-pole alternators installed on British electricity undertakings .

The presence of magnetic material in close proximity to the stator windings, particularly the rotor body and retaining rings, complicates the estimation of the forces ; this point is discussed in Section IV.

The full-load forces on conductors embedded in the stator slots are not large, the torque being carried mainly by the stator iron. Where conductors in different phases occupy the same slot the repulsion forces between them must be restrained by the slot wedges ; these can be designed to have sufficient strength for this duty under maximum-fault-current conditions, and little difficulty therefore arises in the embedded portion of the stator winding due to the short-circuit forces. However, in the end-winding structure which is in air, provision must be made to enable the conductors to withstand the possible displacing forces. Adequate bracing and packing must be provided without unduly impairing the ventilation requirements of the machine.

The resultant force on any coil is that due to its own electro-magnetically produced forces combined with those transferred mechanically from its neighbours through the packing blocks and binding ;

the length of the overhang is therefore an important parameter in determining the total moment on the coil about the core-end, where it may be regarded as being rigidly supported. Modern alternators with high ratings require large-diameter stator bores with correspondingly longer overhangs than those needed on smaller machines. This factor, in addition to the higher current values, must be considered in the design of the bracing to restrain the short-circuit forces associated with large generators.

Analytical Expressions for Forces

For illustration purposes, consider the two layers of a stator end-winding to be developed into two parallel planes as shown in Fig. 2. The point P is located on the outer conductor of the phase-1 band in the upper layer of winding ; the sense of the currents in the various conductors is indicated by the arrows. The diagram is considered to represent the *xz*-plane with the co-ordinate directions as shown by the forces at P. Throughout the cycle there will be a component of force at P, towards the remaining conductors in the phase-1 group, which will vary as I_1^2. Owing to the adjacent phase-2 coils there will be a force proportional to $I_1 I_2$, whose direction and magnitude will vary over the cycle. Similarly, there will be components due to the conductors of phase-3 and due to the phase bands in the lower layer of the winding. In general, the electromagnetic force at any point on a coil carrying current I_1 is given by

$$F_1 = k_{11}I_1^2 + k_{12}I_1I_2 + k_{13}I_1I_3 \quad . \quad . \quad (2)$$

The coefficients k depend upon which conductor is under consideration and the position of the point on the conductor, while the instantaneous values of the phase currents I_1, I_2 and I_3 depend on the short-circuit conditions, i.e., the type of fault and the instant in the cycle at which it occurs. Some investigations on the effect of various types of short-circuit are given in Section V.

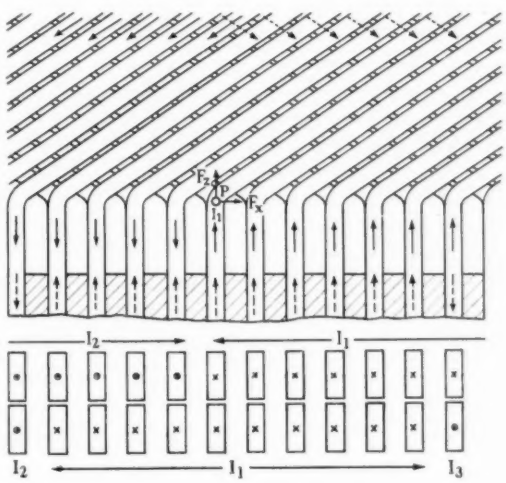

Fig. 2.—Simplified configuration of two layers of end-winding

Previously published analyses of end-winding forces appear to have been confined to approximations with regard to the shape of the coils. Calvert[1] and Zingales[2] consider a group of infinitely-long parallel equally-spaced co-planar conductors and give the expression for the force on the outer conductor of the group. Harrington[3] analyses a configuration similar to that shown in Fig. 2, the two layers of a conical end-winding being considered to be developed into parallel planes with the conductors represented by straight lines ; values of the coefficients k are derived for the component of tangential force in the plane. This treatment is said to be reasonably accurate for a 4-pole alternator whose end-windings lie on cones having half-angles not greater than 25°. Harrington gives results of an investigation made to determine the effect of the stator iron on the magnetic fields in the end-winding, and the conclusion is reached that this is of minor importance over most of the coil length but has some effect on the portion of end-winding nearest to the coil knuckles.

An analysis has been made of the end-winding forces in a particular 2-pole machine for which it was felt that the treatment described in Reference 3 would not be sufficiently accurate. The correct 3-dimensional form of the windings has been

[1] *Calvert, J. F. 'Forces in turbine generator stator windings'. Transactions of the American I.E.E., 1931, 50, p. 178.*

[2] *Zingales, G. 'Azioni meccaniche delle correnti di corto-circuito nelle macchine sincrone'. L'Elettrotecnica, 1953, 40, p. 589.*

Harrington, D. 'Forces in machine end-windings'. Transactions the American I.E.E., 1952, Part III, p. 849.

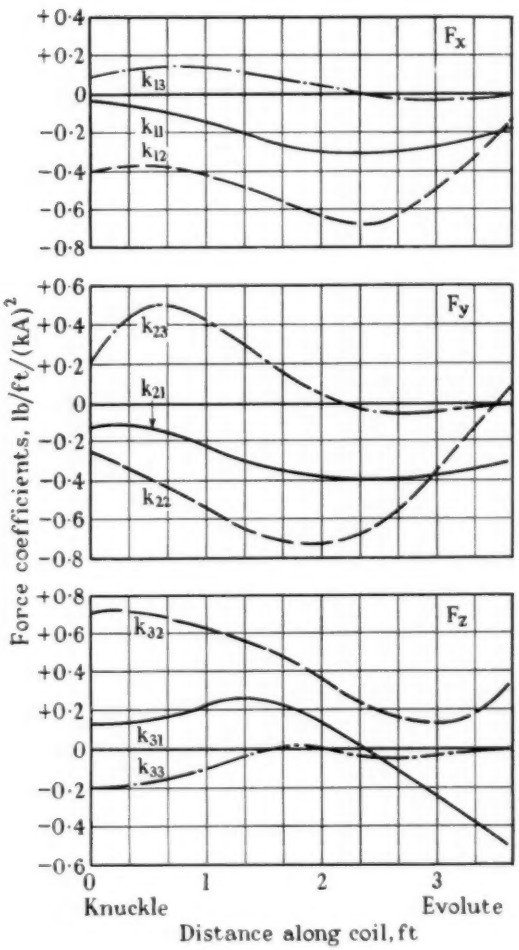

Fig. 3.—Calculated values of end-winding force coefficients for the outer conductor of a phase band on a 2-pole alternator

$$F_x = k_{11}I_1^2 + k_{12}I_1I_2 + k_{13}I_1I_3$$
$$F_y = k_{21}I_1^2 + k_{22}I_1I_2 + k_{23}I_1I_3$$
$$F_z = k_{31}I_1^2 + k_{32}I_1I_2 + k_{33}I_1I_3$$

considered by a method outlined in Appendix 1, and the coefficients k for the forces in the x, y and z directions are shown in Fig. 3 as functions of the length along the curved end-winding conductors.

It is evident that the total displacing force in any given direction will be represented by the area beneath the curves shown, and there will be, in addition, bending moments or couples acting upon the conductor which could also be evaluated from Fig. 3 together with information about the actual shape of the coil. In making any comparison between the figures given in Reference 3 and those shown in Fig. 3 it is necessary to recall that the former relate to a 4-pole machine and the latter to a 2-pole machine and also that F_x, F_y and F_z are the three components of the force at points on the true shape of the coils. In Reference 3 the coil is considered to comprise three sections and the total and average forces on each are given ; no reference is made to the twisting couples previously mentioned or to the effect of the rotor in modifying the forces under actual short-circuit conditions.

From the foregoing it will be clear that the magnetic fields throughout the end-winding during short-circuit will have a somewhat complex distribution. Even if these are calculated and the forces computed, the resulting movement of the coils and the probable damage to the insulation would be almost impossible to evaluate. This is because it is difficult to ascribe quantitative values to the constraints afforded under dynamic conditions by the packing and binding. The problem is still further complicated if it is desired to make due allowance for any ageing in service of the insulating and supporting materials, and to take proper account of the operating temperature of the machine.

Analytical assessment of the damage likely to be produced on alternator windings as a result of a short-circuit therefore presents very considerable difficulties. It is desirable, however, from the viewpoint of both manufacturer and user of electrical plant, that any design should be proved to have sufficient mechanical strength to withstand whatever conditions it may reasonably be expected to encounter in service. It should be possible to establish specifically what can be considered to constitute a satisfactory demonstration of this requirement.

II. INVESTIGATIONS INTO THE CONSEQUENCES OF A FULL-VOLTAGE SHORT-CIRCUIT TEST

The correlation of analytical work with practical experience was investigated with reference to a series of short-circuits under test conditions on the

first of four 60-MW 3-phase 60-c/s 13·8-kV 3,600-r.p.m. alternators for a power station in Canada. The consultants handling the contract on behalf of the purchaser required the generator to be subjected to a solid 3-phase short-circuit from 100% of normal voltage on open-circuit.

Short-Circuit Test Results

In order to check the correct operation of the oscillographic equipment associated with the test, two preliminary short-circuits were carried out, one at 50% and another at 75% of normal voltage, before the specified test from 100% voltage. Following these three short-circuits the alternator was run for several hours on open-circuit above normal voltage. The first indication that damage to the insulation had occurred was obtained when the windings failed to withstand for one minute the final high-voltage insulation test—namely, twice the working voltage plus 1 kV, i.e. 28·6 kV. The windings had previously withstood a test voltage of 30·6 kV between phases and to earth for one minute.

The results of the high-voltage tests were :—

(*a*) The first phase failed on reaching 28·6 kV.
(*b*) The second phase failed at 21·0 kV.
(*c*) The third phase failed after withstanding 28·6 kV for 30 sec. These reduced values of breakdown were undoubtedly a direct result of the short-circuit tests.

On subsequent examination of the end-windings, a few loose ends of the binding material provided the only immediately obvious indication that some slight movement of the windings had taken place.

It is possible that had the operating voltage been 13·2 kV instead of 13·8 kV the windings of two phases might have withstood satisfactorily the corresponding test voltage of 27·4 kV for 1 min. In such circumstances the faulty top-half coil of the third phase would probably have been replaced and any loose binding renovated. Assuming that all three phases subsequently withstood the high-voltage test, the machine would, no doubt, have been accepted, and would have gone into service as healthy. This hypothetical case is mentioned only to emphasize the nature of the acceptance tests and to draw attention to their possible shortcomings. In the case of the machine just referred to, since three coil-sides required replacement it was decided to rewind completely and to obtain in the process as much information as possible regarding the extent of the damage to the insulation resulting from the short-circuit tests.

Measurements taken at the coil knuckles of the upper layer showed some permanent circumferential deflections, and a record was made of the displacement on each of the 60 half-coils in the upper layer ; the average values obtained at the two ends of the stator are shown in Fig. 4. Each half-coil was then electrically isolated and high-voltage tested before removal from its slot. Out of the total of 120 half-coils, 19 failed to withstand voltages to which they had previously been successfully subjected. The location of 16 of these points of coil failure was just beyond the end of the core, clearly demonstrating the susceptibility of this portion of the insulation to damage by shock mechanical displacement of the end-winding structure. One coil was found to have broken down in the slot and on two coils the point of failure was not recorded.

After the removal of the coils from the slots, the insulation was examined at those points of breakdown which could be located. In all the 16 cases referred to, puncture was found to have occurred where the wall insulation had been strained owing to movement of the conductors. There was slight evidence of radial displacement at the coil knuckles, but the major cause of damage appeared to have been circumferentially-directed forces. From the subsequent analyses which have been carried out it appears that it is the latter component of the short-circuit forces which produces the greatest deterioration of insulation strength in windings having a conical configuration. In the investigations reported here, the emphasis has been on circumferential rather than radial or axial forces on the end-winding conductors.

Analysis of Force Distribution

From oscillographic records of the test the appropriate instantaneous values of current were substituted into analytically derived expressions for the circumferential forces adjacent to the knuckles of each coil. From these, the peak magnitudes in both directions attained over the first cycle were calculated as a function of coil position round the

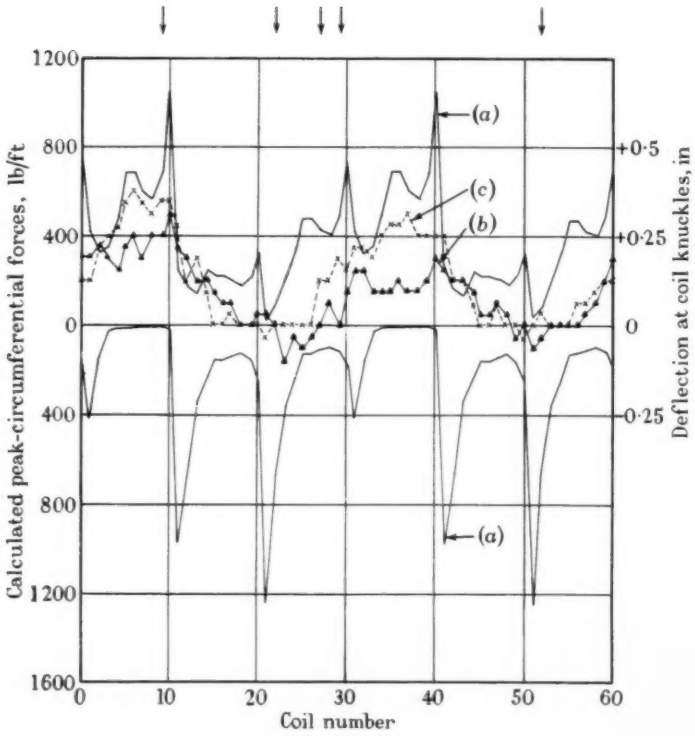

Fig. 4.—Results of short-circuit tests

(*a–a*) Calculated envelope of peak forces at coil knuckles for a particular short-circuit from rated voltage.
Permanent circumferential deflections measured at coil knuckles on :
(*b*) Alternator.
(*c*) Replica stator similarly braced to alternator.
↓ Location in alternator of coils found to have reduced insulation strength following short-circuit test.

periphery, identification being by means of the slot number. The results are shown as an envelope by the two solid lines (*a*) in Fig. 4 which also shows the position of the insulation failures in the upper layer. It has already been pointed out that each coil experiences both its own electromagnetic forces and also a certain transferred effect from the whole end-winding structure. The mean force on any coil thus results from a combination of adjacent values in Fig. 4, and this makes it clear that the general tendency for the upper layer is in a ' positive ' direction, which in this case represents contra-rotational movement. The ' negative ' peaks are opposed to this main tendency so that coils where these peaks occur (e.g. 22, which failed) will be subjected to a series of oscillatory movements of similar magnitudes in either direction, possibly resulting in only small or even no measurable final displacements. This would seem likely to produce at least as much deterioration of the insulation as a number of impulses in one direction, which approximates to what certain other coils would experience (e.g. 9, which also failed). The peak forces shown in Fig. 4 are not in time phase, each occurring at an instant determined by the maximum of an expression in the form of equation (2).

III. SHORT-CIRCUIT TESTS ON AN EXPERIMENTAL STATOR

At the time of the incident previously referred to, consideration had already been given to the evolution of a means whereby the performance of any system of end-winding support could be assessed before its incorporation into a production machine. As already mentioned, it is inherently difficult to evaluate the various constraints involved, and it was therefore felt that any form of scale model would probably not represent correctly the necessary relationships. The suggestion was considered that the conical form of the end winding could be developed, full-scale, into a plane for the purpose of experimental work. It was decided, however, that the constraints would still not adequately correspond to those in an actual machine ; moreover the difficulty of arranging the conductors to obtain all the necessary currents in the correct relative positions and directions would have been an added complication to this form of apparatus. Such a simplified form of construction might be of value if it could first be shown to give results sufficiently similar to those obtained by more accurate reproduction of the true conditions.

An important question arising at this time was whether correct representation of the stator

currents alone would produce forces on the conductors equivalent to those occurring in an actual machine under short-circuit conditions. In an alternator short-circuit the form of the magnetic fields in the end-winding region is influenced by the presence of the rotor, and in particular by the eddy currents in the retaining rings. The modifying effect of the rotor has been investigated and the results appear in Section IV. It is concluded that, compared with conditions produced by the stator currents alone, the initial peak circumferential forces are lower during a short-circuit test, whereas the corresponding radial forces are higher. Since it appeared that circumferential forces were responsible for the major damage caused to the conductor insulation, it was decided that a true representation of the stator currents would permit the most important forces to be reproduced and even amplified ; no attempt was therefore made to include rotor effects during the experimental-winding short-circuit tests.

The Replica End-windings

The final form decided upon for the experimental work consisted of a full-size double-ended replica of the particular end-windings under examination. It was considered sufficient to ensure that the effect of the slot-embedded portion of the coils was adequately represented and that the distance between the end-windings was such as to make negligibly small any mutual electromagnetic effects. Accordingly only 9 inches axial length of core plates was employed, entailing a knuckle-to-knuckle coil length of about 27 inches, but in all other respects the apparatus resembled the complete alternator stator construction. A fabricated framework was employed, and Fig. 5 shows a view of the completed stator replica. Different forms of end-winding support were incorporated at the two ends of the replica ; one of these was precisely as that employed in the alternator mentioned in Section II, where 12 radial brackets located three supporting rings to which the windings were lashed. At the opposite end a different bracing was used, the major modification being to dispense with the three rings and to utilize 24 radial brackets, the coils being lashed to them direct. Since identical forces would be produced at corresponding points at the two ends, a direct comparison would result. A series of short-circuit tests up to the equivalent of one at 80% rated voltage confirmed that the modified end was superior, and it was realized that in order to obtain maximum information from the replica it was desirable to strengthen the other end before subjecting the windings to any greater forces. This was done before continuing the tests up to the 100% value.

The Short-Circuit Tests

The experimental stator was subjected to instantaneous 3-phase short-circuit tests, the current being supplied by a low-reactance switchgear-testing

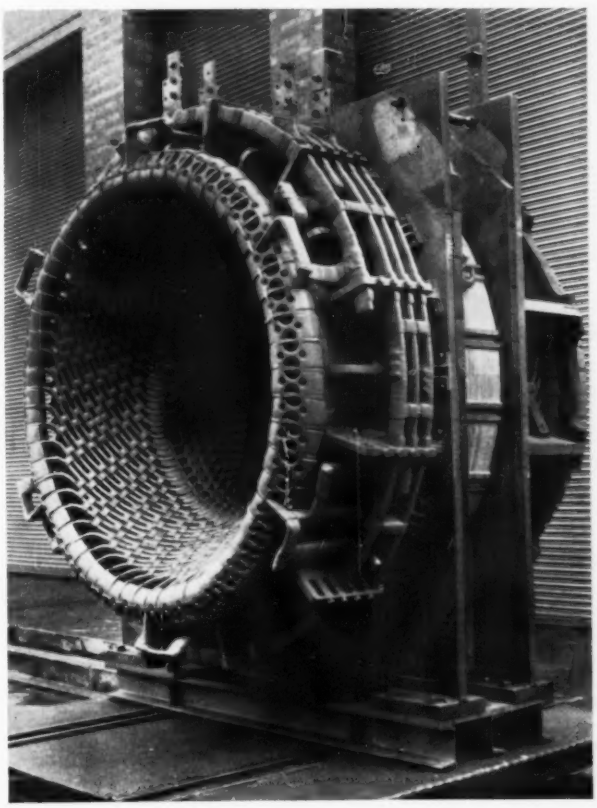

Fig. 5.—The replica stator subsequent to a test with currents equivalent to a full-voltage short-circuit on the alternator

alternator and controlled in magnitude by the addition of external reactance in the circuit. The closure of the switch applying the short-circuit was timed to occur at a point on the voltage wave resulting in the greatest forces at particular positions of the stator winding. A range of current values was chosen, equivalent in magnitude to those resulting from short-circuits at various voltages up to 100% on the original machine. Oscillographic records were taken of all the relevant electrical quantities and also of the output from eight devices indicating the mechanical movement of stator conductors relative to the core-plates and frame. A number of search coils recorded the alternating flux-densities occurring at various points in the end-windings. Numerous measurements were made with vernier callipers and other instruments before and after the tests.

Cinematograph records were made during the short-circuit tests. Two cameras were employed for this purpose, one recording at 64 frames/sec viewing the whole of the end-windings, and the second recording at 1,660 frames/sec viewing the core-end-to-knuckle region of those conductors expected to experience the greatest forces in any particular test.

The movement-recording devices showed that up to currents equivalent to a short-circuit from 50% voltage, elastic deflections occurred on the conductors but no permanent deformations were caused. In further tests with currents equivalent to short-circuits at 75% and 100% voltage the amplitude of the oscillations was greatly increased and some permanent deformation of the conductors resulted. Following the complete series of tests, the windings successfully withstood the full British Standard one-minute high-voltage insulation tests of twice working voltage plus 1 kV, both between phases and to earth.

A record was made of the distortions produced on the replica at the end braced as the original machine, and these are shown as curve (*c*) in Fig. 4 where they may be compared with the measurements taken on the original alternator. It is of interest to note the degree of correlation between these two results. The form and magnitude of the deflections are generally similar, somewhat more distortion having been produced on the replica. It must be borne in mind that a larger number of

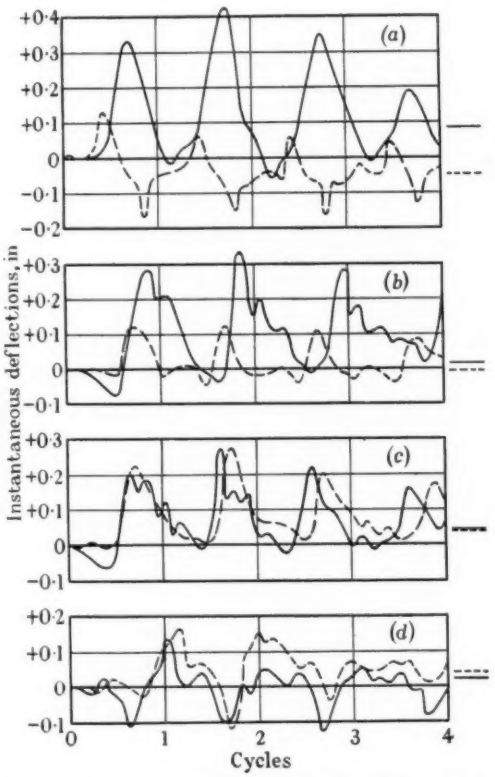

Fig. 6.—Instantaneous deflections measured at points between the knuckles and the core at each end of four coils during 3-phase short-circuit

Coil numbers: (*a*) 41 (11); (*b*) 51 (21); (*c*) 20 (50); (*d*) 1 (31).
Initial 3-phase short-circuit current: 47 kA r.m.s.
Final positions indicated by lines at right:
——— original bracing.
– – – – – – – redesigned bracing.

low-current short-circuits was carried out on the replica than on the actual machine, and also that the rate of decrement was slightly lower during the experimental tests than that recorded on the alternator. As discussed in Section IV which follows, the circumferential forces on the outer conductors of each phase band would be increased by the absence of the rotor.

Instantaneous deflections at points between the knuckles and the core at each end of four coils are shown in Fig. 6 for a test with currents equivalent to a full-voltage short-circuit. The points at which these measurements were made were nearer to the core than those to which Fig. 4 relates, and the

permanent displacements shown do not correspond between Figs. 4 and 6. The peak displacements shown in Fig. 6 are seen to be considerably greater than the final permanent deflections indicated by the lines to the right of the figure, and the complicated nature of the oscillation is evident. The latter may also be appreciated from the high-speed film, which strengthens the belief that analytical methods alone will hardly permit precise evaluation of end-winding performance.

IV. INVESTIGATIONS INTO THE EFFECT OF THE ROTOR

It was evident that there might be differences in the forces experienced by the stator conductors when the same stator currents were produced (*a*) by short-circuiting an alternator running at rated speed and excited to produce some value of terminal voltage, and (*b*) by passing the same currents through the windings from the external source with or without the rotor in position. The configuration of the ordinary conical form of end-winding suggested that the effect of the rotor would diminish continuously from the coil knuckles out to the evolutes. The investigations confirmed this tendency and attention again centred on the knuckle-to-core region of the coils.

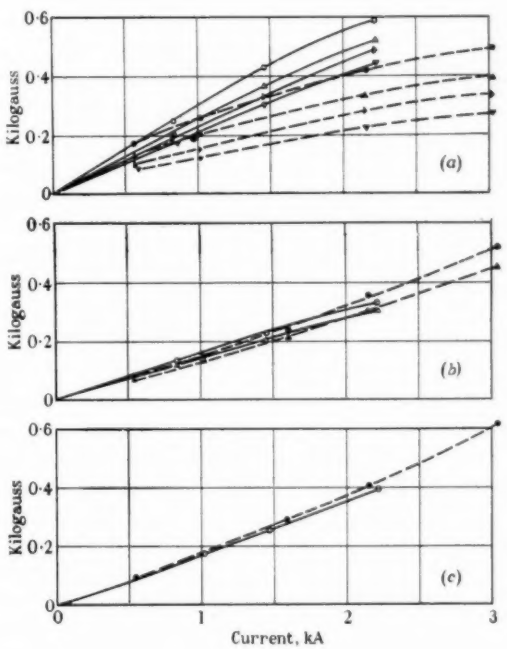

Fig. 7.—Variation of the fundamental alternating components of flux density with stator current

(*a*) Radial components.
(*b*) Circumferential components.
(*c*) Axial components.
● Rotor in position (locked).
○ Rotor removed.

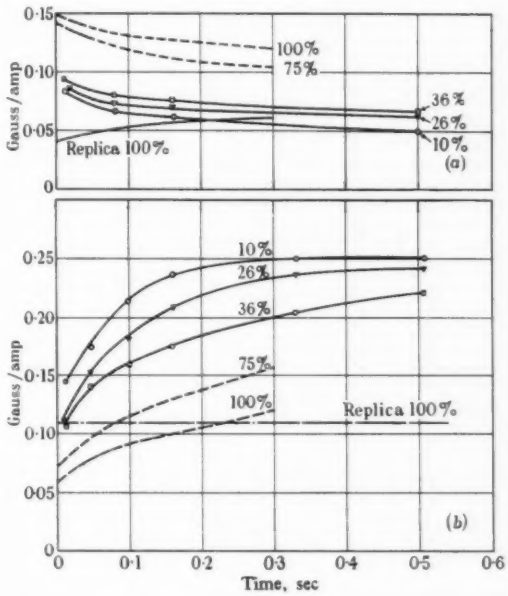

Fig. 8.—Variation of the flux density per ampere of stator current with time, measured at coil knuckles following the application of a 3-phase short-circuit on the replica stator and on a running alternator having magnetic retaining rings

(*a*) Circumferential components.
(*b*) Radial components.
The figures on the curves relate to the percentage of rated voltage from which the short-circuits occurred.

D.C. Component of Stator Current

Fig. 7 shows graphically some measured flux-densities as functions of currents; these were obtained from two series of tests on an alternator stator with currents passed through the windings from an external source. In one series of tests the stator only was used while in the other the rotor was inserted into position but was held so that it was

not free to rotate. It will be seen that the radial flux densities were lower in the presence of the rotor while those in circumferential and axial directions were slightly increased. Eddy currents in the stationary rotor and retaining rings oppose the establishment of radial flux through the rotor by the stator field rotating at fundamental frequency ; the flux path is thus limited to the air-gap and the skin of the rotor iron. These conditions are analogous to those occurring in an actual machine short-circuit so far as the d.c. component of the stator current is concerned, since in that case there is again a relative fundamental frequency between the now stationary field and revolving rotor. The circumferential forces on the stator conductors due to the field of the d.c. component of current would therefore be greater and the radial forces slightly lower on the replica tests than during a machine short-circuit resulting in currents of the same magnitude.

A.C. Component of Stator Current

Two further series of search-coil measurements of flux density were taken during running short-circuits—series (i) up to 36% rated voltage on one of the machines upon which the replica was based, and in which the retaining rings were of magnetic material, and series (ii) up to 100% rated voltage on a 60-MW 11·8-kV 50-c/s alternator in which the retaining rings were of non-magnetic material. The results of series (i) are shown in Fig. 8 where they are compared with corresponding values measured in the replica. It will be seen that the initial values of radial flux density are again lower for the alternator tests. Eddy-currents flow in the main rotor body with an initial magnitude sufficient to maintain constant the flux-linkages existing prior to the short-circuit. A proportion of these currents passes axially into the retaining rings which also carry locally induced eddy-currents. The form of the fields in the neighbourhood of the stator-coil knuckles is determined by the configuration of current paths and iron surfaces, and the magnitudes of the currents vary interdependently in a somewhat complex manner. This case differs from that described under the previous heading (D.C. Component of Stator Current) in that both the rotating field and the rotor must now be considered to be revolving at the same speed, so that the phenomena are essentially similar to the build-up across an air-gap of a flux stationary in space and in the presence of iron circuits. Mathematical analysis of a configuration geometrically similar to the retaining-ring region of the machine at a cross-section through the coil knuckles gave results which agreed well with the measured values. The method employed in the calculation is outlined in Appendix 2. With the decay of the eddy currents, flux penetrates the retaining rings, and where these are of magnetic material a maximum value of radial flux density per unit alternating stator current is reached at the coil knuckles which is greater than that obtained in the absence of the rotor. The flux density per unit current may be limited by saturation of the magnetic paths, and Fig. 8(*b*) indicates the effect that this has on the rate of growth of the radial field.

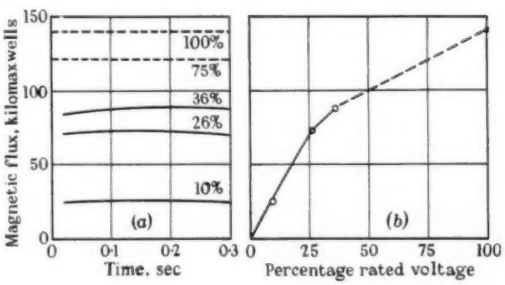

Fig. 9.—The flux entering the retaining ring as a function of time and of applied voltage during 3-phase short-circuits

Fig. 9 illustrates the calculated behaviour of the flux entering the magnetic retaining ring and shows the effect of saturation.

In the results of tests series (ii) carried out on the machine having non-magnetic retaining rings, the flux-density/current curves differed from those shown in Fig. 8 in that the results were practically independent of the magnitude of the current and tended to a limit corresponding to the value given by tests on the stator alone. The initial radial and circumferential components were about 85% and 115%, respectively, of their limiting values, which were reached after only a few cycles of short-circuit current. This time is of the same order as that taken

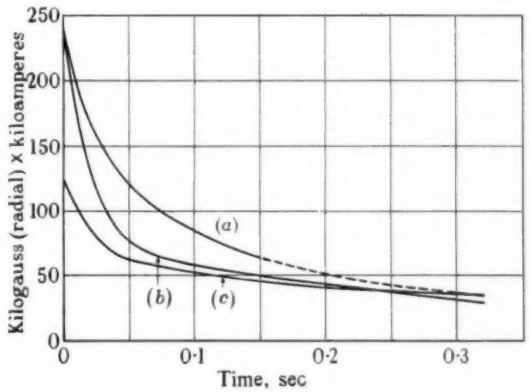

Fig. 10.—Variation of product of current and radial flux density with time during short-circuit from rated voltage

	Current	Flux density
(*a*)	Measured in replica test	Measured in replica test
(*b*)	Measured in alternator	Measured in replica test
(*c*)	Measured in alternator	Calculated value for alternator

for the decay of the eddy currents in the rotor body, and it is evidence of the fact that some of these currents flow into the retaining ring in their passage round one pole pitch to where they re-enter the main rotor body in the opposite axial direction.

Fig. 10 has been prepared from Fig. 8(*b*), and shows, as a function of time, a comparison of the peak circumferential forces calculated to occur on the replica and those in a short-circuit in the alternator from 100% voltage on open-circuit. For the latter figures account has been taken of saturation in the iron paths. It will be seen that the replica tests produce higher initial circumferential forces but that the final sustained value is greater in the alternator. The measurements taken during the replica tests referred to in Section III indicated that, in respect of probable damage to conductors, by far the most significant current values were those in the range equivalent to short-circuits from 75 to 100% voltage. Fig. 8(*a*) indicates that for such short-circuits the peak radial forces acting initially on the stator conductors are larger on the alternator than those reproduced on the replica. The main radial forces are directed outwardly, and the two layers of the end-winding are very effectively supported by brackets bolted to the core. In addition, the normal form of stator construction is such that the winding assembly can be regarded as forming a composite whole which may then be several times stronger to bending in a radial direction than in a circumferential direction.

The results obtained from flux-density measurements on alternators during short-circuit confirm that equal current tests on a replica represent more severe conditions with respect to possible insulation damage.

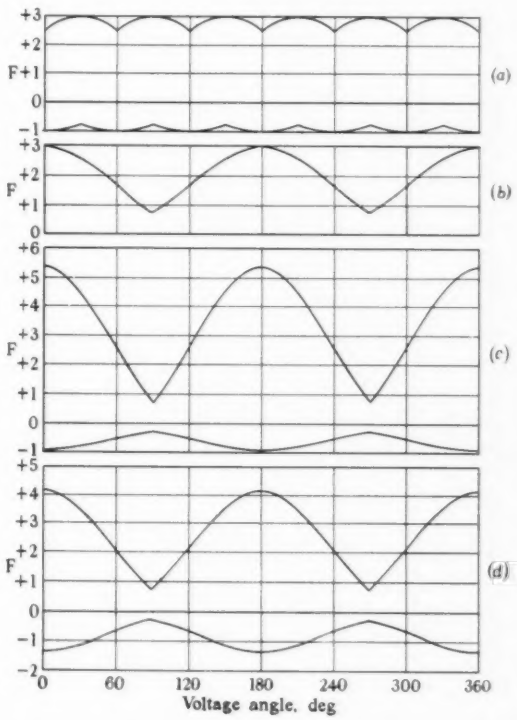

Fig. 11.—Relative values of the peak circumferential forces, F, as functions of the voltage angle, ψ, at which the short-circuit occurs

(*a*) A simultaneous 3-phase short-circuit (ψ refers to $V_{1\text{-}N}$).
(*b*) A phase-to-phase short-circuit (ψ refers to $V_{2\text{-}3}$).
(*c*) Single-phase-to-earth short-circuits occurring sequentially and at the same angle ψ on $V_{1\text{-}N}$, $-V_{3\text{-}N}$, $V_{2\text{-}N}$.
(*d*) Short-circuit from phase 1 at a voltage angle ψ to an existing phase-to-phase fault between phases 2 and 3 which occurred at angle ψ on $V_{2\text{-}3}$.

V. THE EFFECT OF THE TYPE OF SHORT-CIRCUIT

In Section I a description is given of the analytical expressions for the forces occurring at points in the end-winding structure. These take the form of equation (2) and are in terms of all three phase currents. In order to assess the severity of different types of short-circuit it is necessary to ascribe relative values to the k coefficients.

To simplify the problem it has been assumed that equation (2) takes the form

$$F = k_{11}I_1^2 + k_{12}I_1I_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

It can be seen from Fig. 3 that at many points it is reasonable to neglect one coefficient in comparison with the other two. On this basis Fig. 11 has been prepared showing the peak values over the cycle of this expression for force. The curves are directly comparable if the current in a single-phase-to-earth fault is limited by neutral impedance to the same value as that in a 3-phase short-circuit. If the ordinates are considered to be multiples of k_{11} or k_{12} whichever is the larger, the curves then represent the maximum possible values of F. The figures are given as a function of the angle ψ after a voltage zero at which a solid fault is assumed to occur, and include the following types of short-circuit :—

(*a*) A simultaneous 3-phase short-circuit where ψ refers to $V_{1\text{-}N}$.

(*b*) A phase-to-phase short-circuit where ψ refers to $V_{2\text{-}3}$.

(*c*) Single-phase-to-earth short-circuits occurring sequentially and at the same angle ψ on each phase-to-neutral voltage.

(*d*) A breakdown from phase 1 at an angle ψ on $V_{1\text{-}2,3}$ to an existing phase-to-phase fault between phases 2 and 3, which occurred at an angle ψ on $V_{2\text{-}3}$.

It will be seen that except for case (*a*) the forces vary over a considerable range with changes in the angle at which the short-circuit occurs. In practice, the great majority of the faults which may arise are associated with breakdown of solid insulation or flashover in air between conductors. In neither case is it possible for failure to occur at zero voltage (i.e. $\psi = 0$), and as can be seen from the curves, for cases (*b*), (*c*) and (*d*) the forces fall off rapidly with increasing voltage (i.e. as the currents become more nearly symmetrical). In case (*a*) the maximum force occurs when one phase breaks down at a voltage peak, which implies a symmetrical current in that phase if the impedance is purely inductive. The peak force occurs half a cycle later when the remaining two phases both carry an instantaneous current equal to $\sqrt{(3)}I$, where I is the peak value of the a.c. component. It will be noticed that the minimum value of force for case (*a*) is 85% of the maximum, compared to corresponding figures of 25%, 14% and 18% for cases (*b*), (*c*) and (*d*).

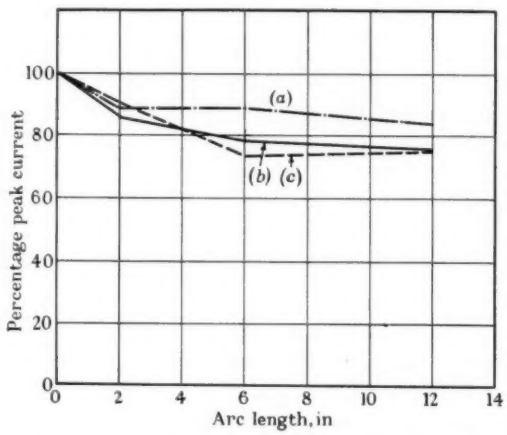

Fig. 12.—*Illustrating the decrease in short-circuit current with arc length*

Peak currents measured in each phase as percentages of those in a solid short-circuit.
(*a*) Blue phase.
(*b*) Red phase.
(*c*) Yellow phase.

An additional factor tending to reduce the current magnitudes is the resistance of the arc which will occur in any form of insulation breakdown. Experimental work has provided a measure of the reduction due to this cause. A test circuit was set up to produce at 11 kV a prospective current of 47 kA resulting from a solid 3-phase short-circuit. It was then arranged that the short-circuits occurred with arcs of varying lengths in the current paths. Since the initiation of the arc was obtained by means of fuse-wire, maximum asymmetry resulted. The peak currents recorded are shown in Fig. 12 as a function of the arc lengths and with the ordinates expressed as percentages of the current in the

solid short-circuit. It will be seen that with arcs of a length likely to be encountered in practice, a current of about 75-80% of that in a solid short-circuit would result. Thus, when the effect of both the arc resistance and the decrease in asymmetry are taken into account, a considerable reduction in current results compared with the theoretically worst case. A reduction to about 66% may be expected, and since the forces vary as the square of the current the corresponding reduction in forces would be to less than half the values shown in Fig. 11.

Another eventuality on power systems which may have to be considered is the possibility of the inadvertent closing of a machine on to a system 180° out of phase. The currents resulting from such an operation are those produced by an effective voltage of twice the normal value acting across an impedance equal to the sum of the machine and system impedances. In the situations where this might result in dangerously heavy currents, the generator will almost always be connected to the system via a generator transformer. An examination of typical reactances for this case shows that even at locations having the highest short-circuit levels the currents will be only about 80% of those resulting from a solid short-circuit on the generator at normal voltage, with corresponding reduction to about 66% of the forces on the conductors.

VI. CONCLUSIONS AND RECOMMENDATIONS

With the present tendency to increase sharply the size of individual units, it would now seem opportune to examine carefully all available records concerning types of faults experienced in service with a view to arriving at a more realistic winding-bracing test before despatch.

Information on such records has been requested from the headquarters staff of the Central Electricity Authority. On the subject of faults on the low-voltage side of generator transformers, including connections, terminals, *etc.*, the instances of phase-to-phase faults which they have recorded comprise the following :—

Ten occasions where flashovers took place on copper-work between the terminals of the generator and the transformer due to various causes such as vermin, water and failure of cable-boxes, etc.

Two cases where breakdowns between phases occurred inside the main generator transformer on the low-voltage side.

One case where the unit auxiliary transformer broke down.

In addition there have been a number of failures between phases on the end-windings of generators.

Since in all cases flashovers are involved, and it is difficult to see how it could be otherwise, any test before dispatch could take the form of a flashover at normal voltage initiated by fuses ; alternatively, a solid short-circuit at reduced voltage could be applied, since such a test may in any case be required to check the alternator reactance.

If, after reviewing available data, it is still felt that the stator windings should be proved capable of withstanding a solid short-circuit at the machine terminals from normal voltage on open-circuit, it may be considered that such a proving test should be applied not to the actual windings but to a short-cored, but otherwise full-scale, replica of the windings as made. A full-voltage short-circuit applied to the actual generator windings, to the customer's satisfaction, might well cause insulation damage which, although not immediately apparent, would lessen the ability of the machine to withstand the less severe but more frequent forces to be experienced under actual fault conditions in service. The use of a replica would ensure that the windings of the machine as delivered would be in a new condition. Assuming that a sufficiently large source of power were obtainable, a replica winding would, in addition, permit testing to destruction to be carried out, thus providing the designers and users of machines with an indication of the margins available. The disadvantage of this procedure would be the cost and the time involved in manufacturing and testing such a replica. It should be clearly understood that the above suggestions are made in the best interest of the customer from the point of view of reliability of machines in service and not to obtain any relaxation in actual bracing effort for the manufacturer.

Available information regarding American practice is that while manufacturers brace machine end-windings to comply with specifications, they do not as a general rule carry out instantaneous short-circuit tests on turbo-alternators. They are, however, prepared to do so should such a requirement be written into the contract, but for reasons similar to those outlined above, customers are not

encouraged to call for such tests. The general indications, therefore, are that in America short-circuit tests are rarely applied.

The film taken of the struggling windings under short-circuit conditions makes clear the undesirability of subjecting the coils and insulation to forces appreciably greater than they are likely to experience under any condition in service.

Acknowledgments

The authors are glad to acknowledge their indebtedness to the Headquarters Staff of the Central Electricity Authority for supplying statistics, and to their colleagues at The English Electric Company's Stafford Works, the Director of Research and the staff of the Nelson Research Laboratories for facilities and assistance in carrying out the investigations reported.

APPENDICES

(1) Calculation of the Coefficients in the Expression for Force (Equation 2)

End-winding dimensions are determined by the bore diameter and length of the stator, the coil pitch and the requirement of suitable spacing between adjacent conductors. In the machine selected for the calculation, both layers of the end-winding formed cones co-axial with the stator, and the spacing between adjacent coils was constant over their length. For the calculation, the conductors were considered to be replaced by line circuits through their centres.

In a plane development of the windings, an approximate expression in polar form for the coil shape was found to be

$$r = R.\varepsilon^{k\theta + n\delta\theta/\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where R, k and δ are constants for one layer of the winding and n defines the position of the coil relative to a given reference coil (for which $n = 0$).

It has been shown[4,5] that the magnetizing force in, say, the y-direction, at a point P, due to current flowing through a line circuit in 3-dimensional space, is proportional to an area swept over by a vector in the xz-plane through P. Consider the projection C′ of a line circuit C on to the xz-plane through the point P. From P draw in the direction of each point Q′ of the projection C′ (corresponding to a point Q on C) a vector of length

$$\rho = \frac{PQ'}{(PQ)^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The area required is that swept over by such vectors, as Q moves from one end to the other of the circuit C.

It is required to calculate, at a number of points P along the length of the reference coil, the magnetizing force due to unit current in all coils of the end-winding. Consider the position of one such point P in the plane development and let it be represented there by (r_P, θ_P); consider also a general point Q, (r, θ), on a coil whose effect at P is being calculated. If the origin is taken at the apex of the cone the co-ordinates of any point (r, θ) become

$$\left.\begin{aligned} x &= r \sin\phi \sin\sigma \\ y &= r \sin\phi \cos\sigma \\ z &= r \cos\phi \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where ϕ is the half-angle of the cone and $\sigma = \theta/\sin\phi$.

Let the co-ordinates of the point P be (x_P, y_P, z_P) and let

$$\left.\begin{aligned} X &= x - x_P \\ Y &= y - y_P \\ Z &= z - z_P \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Then $$(PQ)^2 = X^2 + Y^2 + Z^2 \quad . \quad . \quad . \quad . \quad (8)$$

and for the calculation of H_y,

$$(PQ')^2 = X^2 + Z^2 \quad . \quad . \quad . \quad . \quad . \quad (9)$$

and $$\rho^2 = \frac{X^2 + Z^2}{(X^2 + Y^2 + Z^2)^3} \quad . \quad . \quad . \quad . \quad (10)$$

If $\tan\xi = X/Z$ an increment of area swept over by ρ is given by

$$dA = \tfrac{1}{2}\rho^2 d\xi = \frac{ZdX - XdZ}{2(X^2 + Y^2 + Z^2)^3} \quad . \quad . \quad . \quad (11)$$

Since X, Y and Z are known in terms of r and the co-ordinates of P, eqn. (11) can be written as

$$dA = f(r)dr \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

[4] *Halacsy, A. A. 'Practical calculations of magnetizing forces'. Proceedings I.E.E.* 1950, 97, *Part I*, p. 37.

[5] *Halacsy, A. A. 'The calculation of the magnetizing force'. Transactions of the American I.E.E.* 1952, 71, *Part I*, p. 90.

In general, the expression $f(r)$ is not amenable to explicit integration; the value of A must be obtained by numerical integration between the appropriate limits of r representing the movement of the point Q from one end to the other of the coil C whose effect at P is being calculated. The area A is proportional to H_y at P due to C. Similar treatment enables expressions to be derived for H_x and H_z, and also the components due to the straight coil extensions from the slots, these being directly integrable between suitable limits. The components of H_x, H_y and H_z due to coils carrying currents of the same phase can be combined, and hence the magnetic flux densities B_x, B_y and B_z at P are obtained in terms of the three phase currents I_1, I_2 and I_3.

It is necessary to determine at P the direction cosines cos α, cos β and cos γ of the current I_1 in the reference coil; these can be obtained in terms of r, θ and ϕ, and can be evaluated.

The forces at the point P per unit length of conductor are then given by

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = I_1 \begin{bmatrix} 0 & -\cos\gamma & \cos\beta \\ \cos\gamma & 0 & -\cos\alpha \\ -\cos\beta & \cos\alpha & 0 \end{bmatrix} \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} \quad . \quad (13)$$

But $$\begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \quad . \quad . \quad (14)$$

where $b_{11} \ldots b_{33}$ result from the calculations previously described.

Substituting eqn. (14) in eqn. (13) gives

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = I_1 \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \quad . \quad . \quad (15)$$

i.e., $F_x = k_{11}I_1^2 + k_{12}I_1I_2 + k_{13}I_1I_3$, etc., where $k_{11} = -b_{21}\cos\gamma + b_{31}\cos\beta$, etc.

The terms $k_{11} \ldots k_{33}$ were evaluated at a number of points along the reference coil and the results are shown graphically in Fig. 3.

(2) Analysis of an Equivalent Two-Dimensional System

Fig. 13(*a*) shows a drawing of the end-winding region of a turbo-alternator. The system analysed represents a section through the stator-coil knuckles as indicated. Fig. 13(*b*) shows the equivalent system assumed. The effect of the stator winding is represented by a current sheet located at the mean radius R_3 of the conductors. This current sheet has a sinusoidally distributed m.m.f. equal to the fundamental component associated with the a.c. stator current, I, and given by

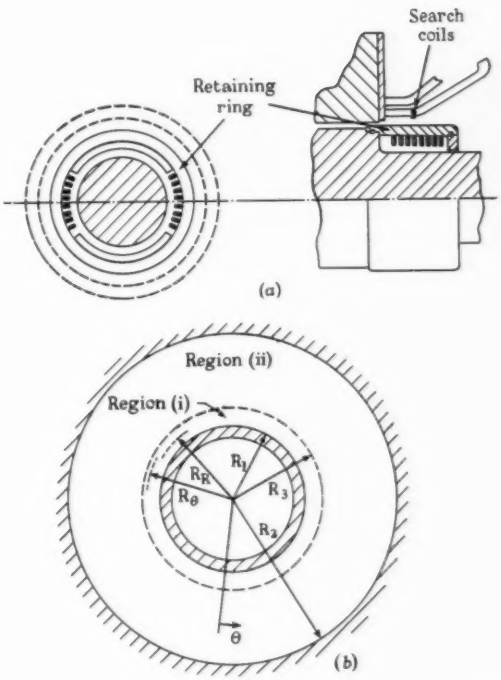

Fig. 13.—Relevant to the analytical representation of an approximate equivalent system

(*a*) Alternator sections at retaining ring.
(*b*) Two-dimensional model to same scale.

$$M = IM_0 \cos\theta \quad . \quad . \quad . \quad . \quad . \quad (16)$$

where M_0 is a function of the stator-winding parameters and has a value of 15·7 gilberts/amp for the machine considered. The magnetic retaining-ring and the proximity of the stator iron are represented by iron surfaces at, respectively, a known radius R_1 and a radius R_2 to be given a suitable value consistent with test results.

It is required to determine the flux distribution in the annular air-space between the two cylindrical iron surfaces in the presence of the concentric current sheet. In regions (i) and (ii) of Fig. 13(*b*) the following equations can be written relating the

radial, B_R, and circumferential, B_θ, components of magnetic flux density at any point (R, θ)

$$\left.\begin{aligned} \frac{\partial B_\theta}{\partial \theta} + B_R + R\frac{\partial B_R}{\partial R} &= 0 \\ R\frac{\partial B_\theta}{\partial R} + B_\theta - \frac{\partial B_R}{\partial \theta} &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad (17)$$

The general solutions[6] for eqns. (17) are

$$\left.\begin{aligned} B_R &= (C_1 R^{n-1} + D_1 R^{-n-1}) \sin n(\theta - \theta_1) \\ B_\theta &= (C_2 R^{n-1} + D_2 R^{-n-1}) \sin n(\theta - \theta_2) \end{aligned}\right\} \quad . \quad (18)$$

the constants having different values in regions (i) and (ii).

The boundary conditions are

$$\left.\begin{aligned} B'_\theta &= 0 && (R = R_1) \\ B''_\theta &= 0 && (R = R_2) \\ B'_R &= B''_R && (R = R_3) \\ B''_\theta - B'_\theta &= \frac{1}{R_3}\frac{d}{d\theta}(M_0 \cos\theta) && (R = R_3) \end{aligned}\right\} \quad . \quad (19)^*$$

Considering these conditions and the current sheet at R_3 with m.m.f. of value $IM_0 \cos\theta$, the solutions to eqns. (18) take the form

$$\left.\begin{aligned} B'_R &= -\frac{IM_0(R_3^2 + R_2^2)}{2R_3(R_2^2 - R_1^2)}\left(1 + \frac{R_1^2}{R^2}\right)\cos\theta \\ B'_\theta &= \frac{IM_0(R_3^2 + R_2^2)}{2R_3(R_2^2 - R_1^2)}\left(1 - \frac{R_1^2}{R^2}\right)\sin\theta \\ B''_R &= -\frac{IM_0(R_3^2 + R_1^2)}{2R_3(R_2^2 - R_1^2)}\left(1 + \frac{R_2^2}{R^2}\right)\cos\theta \\ B''_\theta &= \frac{IM_0(R_3^2 + R_1^2)}{2R_3(R_2^2 - R_1^2)}\left(1 - \frac{R_2^2}{R^2}\right)\sin\theta \end{aligned}\right\} \quad . \quad (20)$$

From search-coil records on the alternator, values of B_R (at $R = R_R$) and B_θ $(R = R_\theta)$ were available corresponding to low currents and steady-state conditions. A particular value of R_2 was found which when substituted in eqns. (20) with the values of R_1, R_3, R, M_0 and I gave results corresponding closely with the test figures. It can be seen from Fig. 13(*b*) that the value of R_2 represents approximately a mean path to the end of the stator iron. Using this value of R_2 and setting $R_1 = 0$ to represent the removal of the rotor resulted in values of B_R and B_θ agreeing reasonably well with those measured on the replica stator tests.

In order to represent the effect of saturation and eddy currents in the retaining ring, a current sheet is introduced at $R = R_1$ having an m.m.f. of value $-\lambda M_0 \cos\theta$. This results in modification of the results in eqn. (20) for region (i), these now taking the form

$$\left.\begin{aligned} B'_R &= \frac{-M_0}{(R_2^2 - R_1^2)} \\ &\left[\frac{(R_3^2 + R_2^2)}{2R_3}\left(1 + \frac{R_1^2}{R^2}\right)I - R_1\left(1 + \frac{R_2^2}{R^2}\right)\lambda\right]\cos\theta \\ B'_\theta &= \frac{M_0}{(R_2^2 - R_1^2)} \\ &\left[\frac{(R_3^2 + R_2^2)}{2R_3}\left(1 - \frac{R_1^2}{R^2}\right)I - R_1\left(\frac{R_2^2}{R^2} - 1\right)\lambda\right]\sin\theta \end{aligned}\right\} \quad (21)$$

or, substituting the numerical values of the parameters

$$B_R = 0{\cdot}260I - 0{\cdot}276\lambda \text{ r.m.s.} \qquad (R = R_R) \quad . \quad (22)$$

$$B_\theta = 0{\cdot}045I - 0{\cdot}142\lambda \text{ r.m.s.} \qquad (R = R_\theta) \quad . \quad (23)$$

$$B_R = 0{\cdot}415I - 0{\cdot}478\lambda \text{ peak} \qquad (R = R_1) \quad . \quad (24)$$

Half the total flux entering the outer surface of the retaining ring per unit axial length is given by

$$\Phi = R_1\int_0^{\pi/2} B_R d\theta = 20I - 23{\cdot}1\lambda \quad . \quad . \quad . \quad (25)$$

or $$\lambda = 0{\cdot}866I - 0{\cdot}0434\,\Phi \quad . \quad . \quad . \quad . \quad (26)$$

Substituting this expression for λ in eqns. (22) and (23) gives

$$B_R = 0{\cdot}021I + 0{\cdot}012\,\Phi \quad . \quad . \quad . \quad . \quad (27)$$

$$B_\theta = 0{\cdot}168I - 0{\cdot}00615\,\Phi \quad . \quad . \quad . \quad (28)$$

* In these equations ′ refers to region (i) and ″ to region (ii).

[6] *Alger, P. L.* '*The nature of polyphase induction machines*'. (*John Wiley and Sons, Inc., New York*, 1951).

From short-circuit tests and search-coil records on the alternator, values of Φ were calculated. These are shown in Fig. 9, and indicate that for any given test, Φ remains approximately constant for times of the order of 0·3 sec following the short-circuit, and also that saturation will impose an upper limit to Φ for the higher short-circuit currents. A pessimistically high value was assumed for this limit, and the flux densities and forces were calculated for a 3-phase short-circuit from 100% rated voltage. The result is shown in Fig. 10 where it is compared with conditions occurring in the replica stator during a test with similar currents.

Electroplated Contacts

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AN ELECTRICAL CONTACT must maintain a sufficiently low resistance consistently under its designed operating conditions in the environments in which it is intended to work, and if necessary it must be capable of withstanding arcing or sparking and resist welding.

To fulfil the first condition of low electrical resistance, in those cases where no cleaning action whatsoever is present the surface of the contact must be kept free from oxides, tarnish films and corrosion products and must be suitably shielded from general dirt. In other cases sufficient cleansing action is inherent in the contact duty, e.g. the third rail in traction systems.

Under some conditions contacts require very little resistance to sparking and arcing, e.g. signal-current contacts in communications equipment. On the other hand, high-power circuit-breakers require contact materials with extreme resistance to power arcs.

With so many factors to consider it is scarcely surprising to find that a large range of alloys and metals in a variety of forms are used for contact materials. Most of these materials have one feature in common, that they employ noble metals either in the pure form or as alloys.

Once a contact design is chosen and a suitable contact material selected, the method of manufacture has to be considered. Electroplating is one of many ways of applying certain metals to provide a contact surface and has its own particular advantages and limitations which must, in some cases, react on the design of the contact if efficient and trouble-free production is to be obtained.

These factors are discussed in detail in this article in order to show how the best use can be made of an electroplating process to achieve the maximum efficiency in production and effectiveness in service.

Mode of Failure of Contacts

(1) In the easiest conditions, the volt-ampere characteristic of the circuit in which the contact has to work is neither too high nor too low, the contact is moderately frequently operated to provide cleaning action and the design provides adequate abrasion to remove any film from the surface (e.g. motor starters for moderate-size machinery). A base metal such as copper, nickel silver or phosphor bronze is frequently adequate as a contact material and it is usual to make the contact from such materials and to apply no surface coating or arcing tip.

If such a contact is placed in an otherwise similar circuit but on a duty cycle where it is required to remain closed for periods of days or weeks, it may give serious trouble on this apparently lighter duty due to tarnish or corrosion films forming at the contact face. These films increase the contact resistance, the temperature rises, oxidation becomes progressive and the position may be quickly reached where the contact is damaged by overheating.

(2) Where contacts have to remain open for long periods and handle small currents at very low voltages, the slightest tarnish film could prevent any current from flowing in the circuit when the contact is closed.

(3) On closing a highly capacitive circuit there is a large current surge which in some circumstances may approach that of a fault current. If the contact material is not sufficiently refractory, welding will take place and the contact fail to open when required.

(4) In low-current D.C. circuits contact material is transferred from one contact to the other in operation. A spike and corresponding crater may be formed and may interlock. If the mechanical force available is not adequate to break off the spike, the contacts will not open.

(5) Contacts may be destroyed because the metal of which they are constructed is melted by the arc produced when they open. It is not necessarily sufficient to use a more refractory material ; good thermal conductivity may also be required.

Choice of Contact Materials

The contact material is chosen to avoid failures of the type briefly described under the previous heading. Of the large range of materials which are available, relatively few are normally electro-deposited. These are the pure noble metals and, to a lesser degree, nickel and copper. They present only a limited range of properties ; in particular none of them show the extremely high resistance to power arcs which is desirable for certain services, or exceptionally high resistance to welding.* The types of service for which they are suitable are indicated in Table I.

TABLE I

TYPICAL APPLICATIONS OF THE PURE NOBLE METALS

Silver	Bolted high-current contacts. Current-carrying contacts on high-power circuit-breakers. Telephone and other relays. Contactor contacts. Snap and knife switch contacts. Isolators on high-current systems.
Gold	Normally-open relays for very low currents. High-frequency low-level switching.
Palladium ..	Slow-speed low-current relays, etc. Most of the applications of platinum can be carried out with palladium.
Platinum	Slow speed and normally-open low-current relays. Most other types of light duty contact where very little metal is required.
Rhodium ..	Signal-current contacts. Light-duty sliding contacts where considerable mechanical wear is expected.

There is a considerable overlap of properties between the majority of noble metals, and usually the choice is partially governed by cost : the metal is selected which can be most cheaply applied and which will perform the services required. It should be noted that when the cost of the solid metal only is considered, the price per unit volume is the criterion, and not the price per unit weight. Table II gives the relative costs of the electro-deposited contact metals on both a weight and a volume basis. Silver is the obvious first choice in cases where the tarnish resistance of the base metal (usually copper) is inadequate. It has the lowest price among the noble metals and the highest electrical and thermal conductivities known. Its main disadvantage is that it forms a sulphide film, occasionally containing a little sulphate, which can interfere with the operation of light contacts.

TABLE II

RELATIVE COST OF PRECIOUS METALS

Metal	Relative Cost (Silver=1)	
	By weight	By volume
Gold	40·2	74·3
Iridium	185	395
Osmium	162	347
Palladium	27·6	31·4
Platinum	87·6	178
Rhodium	146	172
Silver	1	1
Copper	·02	·02

The sulphide film on silver has been stated to be a good conductor, as it apparently allows the passage of electricity provided the circuit voltage and current are reasonably high (i.e. above 50 volts and above 1 ampere). In fact, its conductivity is about ·01 %[1, 2] based on the International Annealed Copper Standard (I.A.C.S.) of 1·7241 microhms per cm^3 at 20°C. It is nevertheless a sufficiently good conductor to allow the passage of some current, and local heating readily breaks the film down to silver, as the sulphide is thermally unstable. A further factor which assists the maintenance of good contact is the fact that silver sulphide is relatively soft and plastic and tends to be squeezed out from the point of contact.

Silver is readily welded under high pressure, the weldability being quite marked at room tempera-

* *It should be noted that it is sometimes necessary to separate the various requirements of a contact, e.g. an arcing contact may be used in conjunction with a separate current-carrying contact.*

[1] *Addicks. 'Silver in Industry' (Reinhold, New York), page 396.*

[2] *G. N. Vinal. Bureau of Standards Science Papers, No. 310 Washington, 1917.*

ture and a drawback where considerable heating is to be expected. This phenomenon is sometimes referred to as 'picking up' under sliding friction. As a result, the pressure density which can be applied is relatively low.

Silver has a fair resistance to bridge transfer (i.e. the transfer of metals from one contact face to another) but in light-duty contacts the spike and crater type of failure may occur. At high currents there is considerable 'splash' on the transferred metal, and no spike is built up.

Palladium is little used as an electro-deposited contact material. There is no justification for this as it would serve well in many circumstances where silver is not adequate, and is less expensive than all the other noble metals. It is completely resistant to sulphide tarnishing, but not completely resistant to oxidation at temperatures above 350°C. Palladium is also harder and more resistant to welding and bridge transfer than silver under most conditions. Its electrical and thermal conductivities are not as good as those of silver or rhodium, but are as good as those of platinum.

Gold would appear to merit attention where only good conductivities coupled with complete freedom from surface films are required. Its electrical and thermal conductivities are next to those of silver in the noble metals, but it is very soft and has a great tendency to cold-weld. A gold 'flash' has been applied to silver contacts to prevent tarnish, but its permanence in the contact area is doubtful even for light duties. It is useful in preventing unsightly tarnish on visible but unimportant portions of less noble metal contacts and is not expensive, as one millionth of an inch is effective for several years if the operating temperature is not high. One objection to its use for this purpose is that its colour 'clashes' with that of other visible components plated with near-white coloured metals.

Rhodium is as cheap as platinum when considered on a volume basis, and is also harder and has higher conductivities. It forms no sulphide films but does form a tenacious oxide at about 900°C which decomposes at still higher temperatures. Rhodium has much the same mechanical properties as electro-deposited chromium. It is hard and brittle and is consequently prone to cracking unless deposited on a reasonably hard, rigid base. Its greatest use is in signal-current circuits, where it is valued for its low 'noise'.

Electro-deposited platinum is only worth considering when a hard, completely tarnish- and oxidation-resistant metal with a certain amount of ductility is required. Its conductivities and hardness are less than those of rhodium and its only real superiority to palladium is its resistance to oxidation at high temperature, and slightly greater hardness.

The other precious metals, osmium, iridium and ruthenium, are more costly and have little value for electrical contacts as pure metals, as they are less stable chemically than the other noble metals. They are used in alloys, which are not commercially electro-deposited.

Some mention must be made of nickel, copper and tin, which are used in the electro-deposited state for bolted contacts. All three suffer from thermal run-away if overheated, and are therefore less suitable than silver for bolted joints where current rating is important. Copper is mainly of interest as a coating for steel when a joint is required to retain good high-current earthing properties. Its use is rare, as the normal protective metallic coatings are as satisfactory. Tin and nickel are sometimes applied to copper and its alloys to improve their tarnish resistance. The most common example of their application is the ordinary soldering tag.

Neither tin nor nickel is satisfactory for a contact surface which has to make or break current ; they are considerably less reliable than copper for this purpose.

Choice of Manufacturing Process

In many cases the best production technique is obvious. For example, certain metals cannot be electro-deposited and must therefore be worked by other means. Again, the shape of the contact may be such that only electro-deposition is feasible. Between these extremes there is a range of circumstances in which there is a choice of several methods of manufacture. Sometimes technical reasons dominate the choice of method ; on other occasions the decision can be based purely on relative cost. In addition to electro-deposition, a contact face may be secured to the body of a contact by riveting,

brazing, soldering, spot welding, or by extruding or rolling a bi-metal section or strip.

Riveting involves weakening the contact by drilling holes, and the rivet itself may not be satisfactory, as the heads tend to be sheared off in some mechanisms.

Brazing and soldering are limited to simple shapes. The former is frequently undesirable as the heating used in the process can adversely affect the mechanical properties of the base-metal contact body or the contact metal itself. Soldering is unsuitable where considerable heat is likely to be generated in service or where mechanical strength is important. Both these processes, together with riveting, very often involve considerable expenditure of time per piece and on this ground alone can often be replaced economically by plating.

Spot welding of contact tips is limited as to size and shape. Where suitable it is a most economic process and plating can rarely compete on cost, though it may do so in some limited cases where the resulting local softening and deformation of the contact body or contact tip is unacceptable.

Bi-metal is an inexpensive method of production but is limited to large-quantity production in shapes which can be rolled or extruded and subsequently sub-divided.

Electro-deposition is the least limited process with respect to the shape of the contact body. The mechanical properties of the base are not impaired and the deposit itself may have mechanical properties which are superior to those which could be obtained by other methods of manufacture. The mechanical properties of some electro-deposited metals are compared in Table III with those of the annealed materials. The most severe limitation on electro-deposits is one of thickness. Of the metals shown in Table III, only silver, copper and nickel can be deposited readily in thicknesses of the order of 0·01 inch or more. The other metals are normally limited to deposits 0·001 inch or less in thickness. Fortunately, silver is the metal most commonly required for medium- and heavy-duty contacts, where considerable thicknesses are normally used.

Characteristics of Electroplating Processes

The most important features of a plating process which affect design are its ability or inability to deposit an even thickness of metal over a complex shape (its 'throwing power'), the thickness of metal which can be deposited satisfactorily, and the mechanical and physical properties of the deposit. Before discussing individual plating processes these factors need further explanation.

TABLE III

PROPERTIES OF SOME METALS, SHOWING THE DIFFERENCES DUE TO ELECTRO-DEPOSITION

Metal	Melting point °C.	Electrical conductivity % I.A.C.S.	Thermal conductivity C.G.S. units	Annealed		Electro-deposited	
				Hardness D.P.N.	U.T.S. lb/sq in	Hardness D.P.N.	U.T.S. lb/sq in
Copper	1,083	100–102*	·94	40	32,000	60–150*	—
Gold	1,063	70–76	·70	32	18,000	60–70	—
Nickel	1,455	20–25	·20	70	46,000	150–450	80,000–250,000
Palladium	1,554	16–18	·17	37	27,500	250–300	—
Platinum	1,773	16·2	·17	37	18,000	400–500	—
Rhodium	1,966	35–37	·21	122	140,000	600–800	—
Silver	960	106	1·00	30	23,000	60–70	30,000–35,000
Hard silver plate ..	960	106	1·00	—	—	100–140	40,000–50,000

* *Acid copper deposits.*

Throwing Power

The throwing power of plating baths is more limited than is generally realised, and varies in a complex manner under varying plating conditions. The primary distribution of metal, i.e. the distribution which would be expected from the simplest predictions based on 100% current efficiency and the plating solution resistivity, is very poor indeed.

The throwing power of a plating solution depends on the manner in which back e.m.f. are produced on the surface of the work, the way in which current efficiency varies with current density, the conductivity of the electrolyte and the dimensions of the plating bath. Many attempts have been made to express the throwing power of a plating bath in terms of a percentage or number, but all the quantitative expressions derived so far are liable to serious errors of interpretation and a qualitative description such as ' good ' or ' fair ' is still the most reliable.

Throwing power must not be confused with covering power, i.e. the ability of the plating bath to deposit *some* metal all over an object. The fact that a coating can be seen in deep recesses is in itself no indication of good throw. Good covering power is, of course, essential before good throwing power can be obtained.

Limits to the Thickness of Deposit

Little theoretical information is available on precisely what limits the thickness of a metal which can be deposited before the deposit becomes rough, spongy or otherwise unsatisfactory. With some plating solutions the smoothness of the deposit improves as plating continues, and the first limitation is cost or change in shape of the object being plated. The thickness which can be deposited is a feature of the individual plating solution.

Plating baths which have good throwing power but which are limited on deposit thickness are often used where possible in preference to other solutions which give heavy deposits and have poor throw.

Physical Properties of Deposits

The physical properties of deposits can vary greatly with conditions of deposition. The hardness is usually greater than that of the annealed material, and is in some cases in excess of that normally given by cold working.

The electrical and thermal conductivities of the deposit may not be as good as those of the normal material. Care must be taken in choosing a plating process for contact work to ensure that high-purity deposits are produced. Bright plating baths have to be regarded with suspicion unless it is known that the brightener does not co-deposit with the metal. Brighteners are not the only source of trouble, as the chemicals normally present in the plating bath may also co-deposit in harmful quantities.

Plating Processes

The main features of the more important plating processes are given in Table IV.

Silver Plating

Silver has been electro-deposited for well over a hundred years for decorative purposes, and more is known about its deposition than that of any other noble metal. Its use for electrical contacts is comparatively recent. At one time the only type of bath available was that used in the cutlery trade. Lately, solutions have been developed which are more suited to heavy, rapid deposition, and have considerably widened the field on medium- and heavy-duty contacts ; this is particularly fortunate, as silver is the most suitable metal for this class of work, where heavy deposits are often required. It is virtually the only contact metal electro-deposited for heavy electrical engineering purposes.

The silver plating baths are economical to run and easy to operate. Chemical decomposition of the solution is slow, and replenishment of the bath by dissolution of the anodes is the normal practice. Solutions have virtually an indefinite life with reasonable care, and the author has seen a bath in satisfactory operation which was claimed to be 60 years old. The rate of deposition can be satisfactorily controlled, as the cathode efficiency is 100%.

Palladium Plating

Palladium cannot be deposited in great thicknesses, and its use is therefore limited to light duties. The modern plating solutions are easy to handle and the rate of deposition is certain. The solution cannot be replenished by anode dissolution, and the metal has to be added to the bath

TABLE IV

MAJOR CHARACTERISTICS OF THE INDUSTRIAL PRECIOUS-METAL PLATING BATHS

Metal	Approximate (max.) thickness of deposit (inches)	Throwing power	Ease of operation	Remarks
Silver	0·05	Good	Good	Rate of deposition easily controllable but traditional bath slow. Rapid solutions available.
Palladium	0·0005	Moderate to good	Good	Rate of deposition certain but slow. Solution very stable.
Gold	0·001	Good	Good	Rate of deposition somewhat unreliable.
Rhodium	0·001	Fair	Moderate	Deposits up to 0·002 inch have been claimed under special conditions. Careful control necessary to achieve known thickness.
Platinum	0·0005	Moderate	Fair	Solution needs careful control. Rate of deposition certain if bath working properly. Process needs constant watching.

in the form of salts. Nevertheless, deleterious chemicals do not accumulate in the solution, as the breakdown products of the salts are water and volatile gases.

Gold Plating

Commercial gold solutions are most suited to thin decorative plating. This is of little consequence as only 'flash' deposits are normally desired. The rate of deposition is somewhat uncertain, as the current efficiency of the solution is variable. Replenishment by anodic dissolution is possible but is not normally practised, most operators preferring to add the metal as salts and replace the solution occasionally when it becomes too contaminated with decomposition products.

Rhodium Plating

Rhodium is unique in that it is used as the pure metal only in the electro-deposited state, although there are some applications for rhodium-containing alloys. It is an extremely hard and quite brittle metal and is not suitable for normal methods of fabrication.

Careful control of rhodium plating solutions is necessary if the thickness of the deposit is to be controlled with reasonable certainty. The plating solution is stable, but anodic replenishment is not possible and this results in a build-up of free sulphuric or phosphoric acid in the solution. The metal is added as a solution of the sulphate or phosphate. The bath is not as easy to handle as the silver, gold or palladium baths.

Platinum Plating

Platinum is not an easy metal to deposit satisfactorily. Attempts have been made to deposit platinum from solutions similar to those used for palladium, but these have not proved commercially successful. The bath at present used has very serious disadvantages and limited life. Slight traces of cyanides cause the deposition of metal to be inhibited almost completely, and the bath has an unhappy characteristic of suddenly changing from depositing metal at 100 per cent. efficiency to depositing little metal at all. The remedy is to turn off the current and allow the bath to stand for a time before continuing to plate. Good results can be achieved with care but the process is naturally unpopular.

Copper, Nickel and Tin Plating

These metals can be deposited very satisfactorily from a large selection of plating solutions. They jointly account for the vast majority of all the metal which is electro-deposited in the world to-day. Apart from the somewhat limited throwing power of the nickel plating baths at present in

commercial use, there is no particular limitation on any of the processes. It is worth noting that copper and nickel may be deposited with a range of mechanical properties and in thicknesses up to 0·25 inch if suitable control is exercised, and these metals find limited use in electro-forming contacts with internal precious-metal facings. The procedure is to deposit the desired surfacing metal on the male forming pattern and to follow this by a heavy deposit, usually of copper, after which the pattern is extracted. This method is particularly suitable for the manufacture of wave-guides.

Design Features

Plating should be considered as early as possible in the design of a contact, particularly where heavy deposits are likely to be required. If this is not done, and plating is added as an afterthought, the results may be disappointing or the requirements impossible to fulfil.

Shape of a Contact

For the best and most economic results, the contact area should be an external convex surface, with no sharp edges or corners. This is an ideal, but it can be approached quite often. Such a contact will acquire the thickest deposit on its working surface, and the deposit can be confined to the contact surface without special anode arrangements if the deposit is a heavy one. If a female contact is used it should, where possible, be made up of a number of elements which can be treated individually. Large parts which require plating on small areas only are best avoided, as they reduce the output of the plant and increase the amount of labour expended on 'stopping off' the unplated area.

The shape of a contact may be such that it cannot be jigged or wired easily (e.g. a sphere). In such cases poor electrical contact with the suspender in the plating bath may result in thin deposits, or the contacts may fall off the suspension during treatment. This may result in the destruction of the contact, as it may be too badly attacked by acids or other chemicals to be of further value.

Solution Traps

Certain methods of jointing such as riveting and spot welding inevitably lead to trapping of solutions in the joint. This can cause trouble with contaminated plating solutions and subsequent seepage and corrosion of the contact after it has left the plating shop. Similarly, braded or laminated flexibles should not be attached to an assembly before plating.

A problem sometimes arises with tubes which require plating externally. The inside of the tube may not be covered completely with the deposit and attack by the plating solution is usual in such cases. This may not seriously injure the component, but if repeated frequently it is almost certain to cause trouble with the plating solution ; the resultant cost may be hundreds of pounds. This difficulty is easily avoided by sealing the ends of the tubes with a soldered or brazed plug. Bunging the ends with corks in the plating shop is not a satisfactory answer, as they may blow out on entering a hot solution, or a cold solution may be drawn in slowly by changes in air pressure inside the tube.

Base Metals

The base metals used for contacts are almost invariably copper alloys. Most of these are easy to plate, but berylium copper and some of the high-tensile brasses (manganese bronzes) may cause difficulty as they are not always recognised by the plater and require slight variation from the usual treatments. Occasionally a contact is made from an aluminium alloy, and in such cases it is most desirable that the silicon and, particularly, magnesium content should be as low as possible. Some high-magnesium alloys are almost impossible to plate satisfactorily.

The contact should be as homogeneous as possible. The use of even two copper alloys in the same assembly can seriously reduce the chance of a completely satisfactory job, while some combinations are virtually unplatable. Difficulties of this type are fortunately rare.

Planning

Usually an article is plated after it is otherwise completed. When a protective or decorative deposit is to be applied this is in most cases correct, but when an engineering deposit is required it is sometimes the worst and often not the best proce-

dure. It is impossible to generalise sufficiently to cover a substantial proportion of cases, and consultation with the plater is the best approach to this problem.

A frequent cause of trouble is the incomplete removal of mill scale, brazing and welding fluxes, or foundry sand from articles before they are machined. The plater is then forced to use long pickling times in strong acids (or even shot-blasting) in order to obtain an adequately clean surface on which to plate. The effect on dimensional tolerances can be most unsatisfactory. This matter should never be left to chance but heavy cleaning should be planned as a separate operation after welding and brazing, before final machining.

A production batch should, if possible, be adequate to form at least one load for the plating bath. Plating part or mixed bath loads leads to very poor productivity and doubtful thicknesses.

Future Developments

Electroplating is likely to remain much more of an art than a science for some years to come. The scientific development in this field has made considerable headway in the last two decades and is continuing at an increasing pace ; much of this work has resulted in laboratory processes which could be further developed and used for production if an adequate demand existed.

One of the perennial problems of the electroplater is that of producing local deposits limited to a defined area. One approach to this is the traditional ' stopping-off ' procedure. More recently, attention has turned to the old plater's practice of ' doctoring' local areas of a deposit by applying an anode wrapped in a rag soaked in plating solution. A successful process of this type (brush plating) has been developed for depositing thin films of silver on busbar joints and other bolted connections ; it has now been in large-scale use for several years

TABLE V

USEFUL BINARY CONTACT ALLOYS WHICH HAVE BEEN ELECTRO-DEPOSITED

(After Faust,[3] with additions since 1940)

	Cobalt	Copper	Gold	Iridium	Lead	Molybdenum	Nickel	Palladium	Platinum	Silver	Rhodium	Tungsten
Cadium			X							X		
Cobalt							X			X		X
Copper			X				X	X	X	X		
Gold							X		X	X		
Iridium								X	X	X	X	
Lead										X		
Molybdenum												
Nickel										X		X
Palladium									X	X	X	
Platinum										X	X	
Silver											X	
Rhodium												

[3] *C. L. Faust. ' Alloy deposition.' Trans. Electrochem. Soc.*, 1940, *Vol. 78, p. 73.*

and is a technical and economic success. Several other processes of the same type have been on the market from time to time but all have had severe economic disadvantages, and deposit thicknesses have been limited.

Alloy plating has been gaining ground industrially for some years. It has not yet found favour for electrical contacts because no adequate demand exists for any of the alloy plating baths which might be useful for contacts. Table V illustrates the extent of the laboratory work carried out, and some of these processes are successful for commercial decorative plating. The work of Brenner[4] on alloys of nickel and cobalt with tungsten is of special interest, as it offers the possibility of electro-depositing arcing contacts. His nickel-tungsten process produces alloy containing up to 40 per cent. tungsten, and is not difficult to operate in the laboratory. The main objection to it is the amount of ammonia fume evolved.

A method of depositing gold alloyed with nickel, copper and silver, recently described by Gardham[5], enables the proportion of the metals in the alloy to be varied by turning a knob. The principle of the method is suitable for commercial exploitation.

Tertiary alloys have not been neglected, and silver-platinum-gold, silver-platinum-palladium and silver-platinum-copper have been deposited in the laboratory[6]. The object of the investigation was to produce a low-cost alloy identical in appearance with silver but completely resistant to tarnishing. The processes are not suitable for commercial development, but the investigation considerably narrowed the range of possible solutions by eliminating a large number of impossible approaches.

Electroplating has conventionally been carried out using smooth D.C. or raw rectified A.C. Recently, unsymmetrical A.C. has been coming into use for this purpose. It has attracted much attention and has been shown to have many advantages. The inclusion of this ' partial reverse (P.R.) current ' plating as a ' future ' development is justified only by the fact that it is certainly in its infancy and is not yet entirely satisfactory for general use.

[4] *A. Brenner. Proc. 3rd International Electrodeposition Conference, London*, 1947.
[5] *Gardham. Trans. Inst. Metal Finishing*, 1954, *Vol.* 31.

[6] *Graham, Heiman and Pinkerton. ' Plating ', Dec.* 1948, *Jan. and Feb.* 1949.

RECENT 'ENGLISH ELECTRIC' TECHNICAL PAPERS

JAEGER, Ch., Dr. es Sc. tech., Consulting Engineer to the Hydraulic Department of The English Electric Company, and Special Lecturer at the Imperial College of Science and Technology, London. *Present trends in the design of pressure tunnels and shafts for underground hydro-electric power stations.* Institution of Civil Engineers, London, 16th November, 1954.

A number of underground power stations were built before the 1939-45 war, but nearly all of these were in the continent of Europe. The tremendous development of this type of design in all parts of the world is typical of post-war conditions. It is due partly to improvements in tunnelling technique and partly to the necessity for greater concentration of hydro-electric power in a few large stations. The Paper lists the types of underground power stations according to their characteristics, and discusses the problems raised by these new structures.

After a short discussion on the hydro-dynamics of underground stations, the main problems dealt with concern the design and construction of pressure tunnels and shafts. Strain and stress distribution in the rock and in the concrete lining, and stresses in the steel lining, are analysed. The more modern theories are summarised, the danger of outside water pressure is stressed and the effect of rock grouting is discussed. The exposé leads progressively to an analysis of the modern ideas on pressure-tunnel design.

Underground power houses are, from a purely technical point of view, merely a paragraph out of a wider chapter on tunnel construction. Underground power houses are analysed from the point of view of overall dimensions, volume of excavation, design technique, and machinery.

WARRINGTON, A. R. van C., A.C.G.I., B.Sc., Fel. A.I.E.E., Engineer and Manager, Relay Department. *Economies in the use of protective relays.* Read on behalf of the author by L. L. Brinkworth, Chief Engineer, English Electric Company of South Africa (Proprietary) Ltd, before the South African Institution of Electrical Engineers at Kelvin House, Johannesburg, in February 1955.

Automatic protection of power system equipment by protective relays is a necessary insurance against the cost of damage and service interruptions due to faults. It is unwise to reduce the cost of this protection by using fewer or inadequate protective relays, but considerable saving in the overall cost of protection can be effected by using protective schemes that require less engineering time, and relays that require less maintenance and testing time.

There are two main sources of expense in protection; (*a*) the initial cost of buying, engineering and installing the relays, and (*b*) their maintenance thereafter. The Paper is divided into four parts, dealing respectively with; the initial expense, the design of relays for minimum maintenance, the speed-up of testing and maintenance in order to save man-hours, and aspects affecting all the foregoing.

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